Forest Research

Carbon impacts of biomass consumed in the EU: quantitative assessment

Final report, project: DG ENER/C1/427
Part A: Main Report

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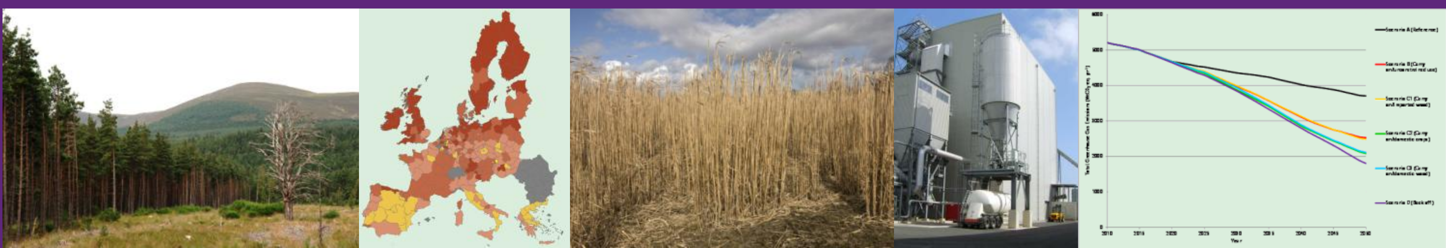

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See Part B of this report for appendices of supporting data, results and worked examples

Executive Summary

Introduction

This report has been prepared in fulfilment of a European Commission project, ENER/C1/427-2012 on 'Carbon impacts of biomass consumed in the EU'. The principal objective of this project is to deliver a qualitative and quantitative assessment of the direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios focussing on the period to 2030, but also extended to 2050, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions.

The quantitative assessment of this project has been undertaken by applying the methods of consequential life cycle assessment (LCA). The project objective was translated into an LCA "question" or goal, which was stated as *"to quantify the global emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources, resulting from implementation of possible EU policies, represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050".* Based on this specific question, changes have been evaluated in global GHG emissions consisting of direct GHG emissions from fossil fuel combustion and other prominent sources, carbon sequestration, biogenic carbon emissions, indirect GHG emissions and relevant counterfactuals associated with the use of bioenergy.

Scenarios for biomass use in the EU

The quantitative assessment has involved evaluating the impacts on GHG emissions associated with six scenarios for the supply and consumption of biomass for energy within the EU region.

A **Reference Scenario A** represents the case where *existing policy targets* for renewable energy consumption and reductions in GHG emissions, set for 2020, should be met, but no further explicit policies or measures are taken to go further than the 2020 targets.

Four decarbonisation scenarios, **'Carry on' Scenarios**, represent cases in which policies and measures with regard to renewable energy consumption and reductions in GHG emissions go further than the existing 2020 targets, by setting more ambitious targets for 2030, involving increased use of bioenergy:

- **Scenario B ('Carry on/unconstrained use')** – highest use of biomass for energy, from all sources, i.e. with limited constraints on the types of sources consumed
- **Scenario C1 ('Carry on/imported wood')** – emphasises the (relatively unconstrained) consumption of imported forest bioenergy
- **Scenario C2 ('Carry on/domestic crops')** – emphasises the consumption of bioenergy from energy crops and agricultural biomass grown in the EU region, allowing for sustainability criteria to be applied to biomass sources.

- **Scenario C3 ('Carry on/domestic wood')** – emphasises the consumption of forest bioenergy, supplied from forests in the EU region allowing for sustainability criteria to be applied to biomass sources.

A further decarbonisation scenario, **Scenario D ('Back off')**, represents a situation involving the same ambitious targets for 2030 as in the 'Carry on' Scenarios. However, the consumption of bioenergy for meeting these targets is de-prioritised post 2020.

Approach to development of scenarios

The development of scenarios for bioenergy use in the EU required a holistic approach to the quantitative assessment of the scenarios developed in this project. This involved the assessment of changes in the energy system in relation to energy sources and conversion technologies associated with each of the scenarios. As a consequence, the GHG emissions impacts assessed in this project reflect the contributions of many changes in the energy system, alongside contributions made by bioenergy sources. The development of the scenarios also involved a number of key assumptions and criteria. The modelling approach and key assumptions and criteria are described more fully in a subsequent discussion of how this project has been carried out.

Key findings of the quantitative assessment

All scenarios achieve significant reductions in total annual GHG emissions, including those scenarios involving increased bioenergy consumption in the EU

An assessment of the main quantitative results for all six bioenergy scenarios developed in this project, based on consideration of trajectories of total annual GHG emissions over time, indicates that the trends for all trajectories are consistently and significantly downwards, as shown in Figure 1 and Table 1.

These results for total annual GHG emissions require very careful interpretation. In particular, it is important to recognise that the projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. This raises the question of whether the overall contribution to these results for total annual GHG emissions due to bioenergy is helping to reduce GHG emissions or is increasing them. The assessment of the contributions made specifically by bioenergy required further detailed analysis in order to discern their influence on overall results for total annual GHG emissions. This is the subject of a subsequent discussion of choices amongst scenarios, and sources of differences.

Figure 1 Trajectories of total annual GHG emissions ($MtCO_2$-eq. yr^{-1}) over the period 2010 to 2050 for all scenarios

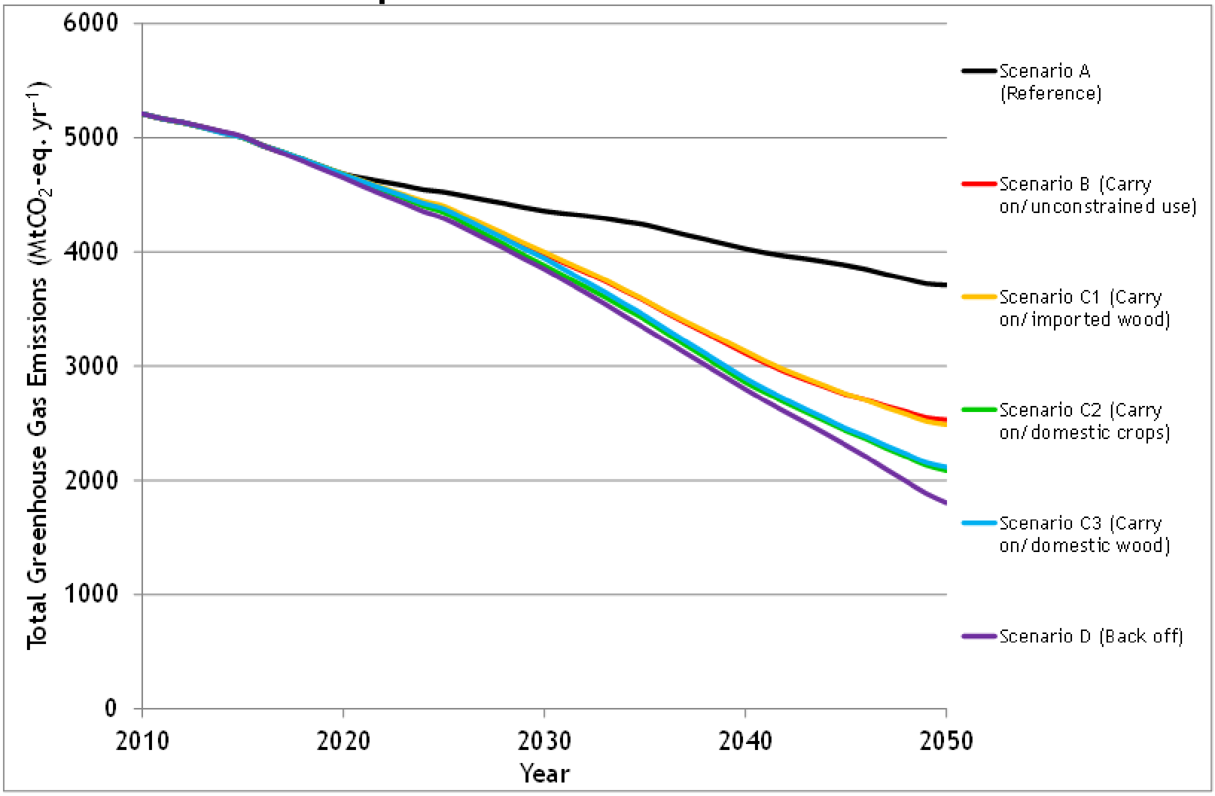


Table 1 Total annual GHG emission reductions in 2020, 2030, and 2050 ($MtCO_2$-eq. and %)

Scenario	Reduction in total annual GHG emissions for year, relative to 2010					
	2020		2030		2050	
	$MtCO_2$	%	$MtCO_2$	%	$MtCO_2$	%
A (Reference)	528	10.1	850	16.3	1 499	28.8
B ('Carry on/ unconstrained use')	537	10.3	1 228	23.6	2 678	51.4
C1 ('Carry on/imported wood')	530	10.2	1 211	23.2	2 721	52.2
C2 ('Carry on/domestic crops')	534	10.2	1 328	25.2	3 123	60.0
C3 ('Carry on/domestic wood')	535	10.3	1 265	24.3	3 093	59.4
D ('Back off')	560	10.8	1 359	26.1	3 404	65.4

Notes to Table 1:

1 These results represent contributions to reductions in global GHG emissions potentially arising from EU energy policy, i.e. GHG emissions due to EU policies occurring both within and externally to the EU region. Hence, these results should not be confused with an assessment of whether internationally agreed targets for emissions reductions within the EU region (subject to specific reporting conventions or accounting rules) may or may not be met.

2 Total GHG emissions estimated for the base year are 5208 $MtCO_2$-eq. yr^{-1}.

De-prioritising bioenergy could lead to significantly higher overall energy system costs with significant logistical challenges

As shown in Table 2, this assessment identified that, whilst the 'Back off' Scenario D can lead to somewhat bigger GHG emissions reductions than the high-bioenergy 'Carry on' Scenarios, it also stands out as significantly more expensive, in terms of cost performance, compared with all of the 'Carry on' Scenarios. It follows that future energy demands can be met without prioritising bioenergy, but most likely at much higher cost and with significant logistical challenges. However, these results for cost performance require very careful interpretation, since the assessment of costs is for the energy system only and is not comprehensive. It must also be appreciated that there are logistical challenges associated with the high-bioenergy 'Carry on' Scenarios as well as the 'Back off' Scenario D. These points derive from the modelling approach and key assumptions and criteria adopted in this project, and are described more fully in the subsequent discussion of how this project has been carried out.

Table 2 Cost performance of bioenergy scenarios in 2030-2050 (% GDP, €/tCO_2)

Scenario	Marginal energy system cost (% of GDP) for year		Marginal carbon price (€/tCO_2) for year		Average GHG reduction cost 2010-2050 (€/tCO_2)
	2030	2050	2030	2050	
B ('Carry on/ unconstrained use')	0.18%	0.90%	48	196	122
C1 ('Carry on/ imported wood')	0.19%	0.89%	43	147	125
C2 ('Carry on/ domestic crops')	0.18%	0.91%	43	160	96
C3 ('Carry on/ domestic wood')	0.20%	0.91%	38	138	100
D ('Back off')	0.63%	1.59%	53	310	183

It should be stressed that the poorer cost performance of Scenario D, in comparison with the 'Carry on' Scenarios, does not imply that the other renewable energy sources used in place of bioenergy in Scenario D must cost significantly more than bioenergy sources. Rather, the higher costs of Scenario D are associated generally with challenges involved in meeting the targets set for levels of renewable energy consumption and GHG emissions reductions, whilst also de-prioritising the consumption of bioenergy.

The modelling of the high-bioenergy 'Carry on' Scenarios in this project has involved identifying a cost-optimal mix of energy sources and conversion technologies for energy supply in the EU region. This involves selecting all the cheapest sources of energy and conversion technologies needed to meet the final energy demand. In the 'Carry on' Scenarios, most of the biomass specified as available for consumption is selected because of its relatively low cost, along with other low-cost sources of renewable energy, for example, low-cost wind power generation.

When the use of bioenergy is constrained (such as in Scenario D), the remaining available lower-cost energy options are not sufficient to meet the targets set for renewable energy supply and GHG emissions reductions. Hence, higher-cost options also need to be included as part of actions taken (for example, wind power installations in low-wind areas, with higher associated costs).

Choices amongst bioenergy sources lead to variable impacts on overall GHG emissions

As shown in Table 3, for all of the decarbonisation scenarios, there is a similar and significant reduction in the contribution to total annual GHG emissions due to 'Fossil' GHG emissions, compared with Reference Scenario A, of between 454 and 460 $MtCO_2$ yr^{-1}. The changes in the contributions to total annual GHG emissions due to 'Bioenergy' emissions in the decarbonisation scenarios, compared with Reference Scenario A, are variable. For the 'Back off' Scenario D, the contribution is reduced by 95 $MtCO_2$ yr^{-1}, reflecting the lower use of bioenergy under this scenario after 2020, due to its deprioritisation.

In contrast, the contributions due to 'Bioenergy' are generally increased under the 'Carry on' Scenarios, but are variable, being highest at 108 $MtCO_2$ yr^{-1} for Scenario C1 (which has the largest relative contribution from imported forest bioenergy sources), and lowest (negligible change) for Scenario C2 (which has the largest relative contribution from domestic sources of agricultural biomass).

Table 3 Changes in total annual GHG emissions in 2030 compared to Reference Scenario A ($MtCO_2$-eq. yr^{-1})

Scenario	GHG emissions ($MtCO_2$-eq. yr^{-1})			
	Fossil	Bioenergy	Other	Total
B ('Carry on/ unconstrained use')	-456	77	2	-378
C1 ('Carry on/ imported wood')	-458	108	-11	-360
C2 ('Carry on/ domestic crops')	-460	0	-17	-478
C3 ('Carry on/ domestic wood')	-460	64	-18	-415
D ('Back off')	-454	-95	41	-508

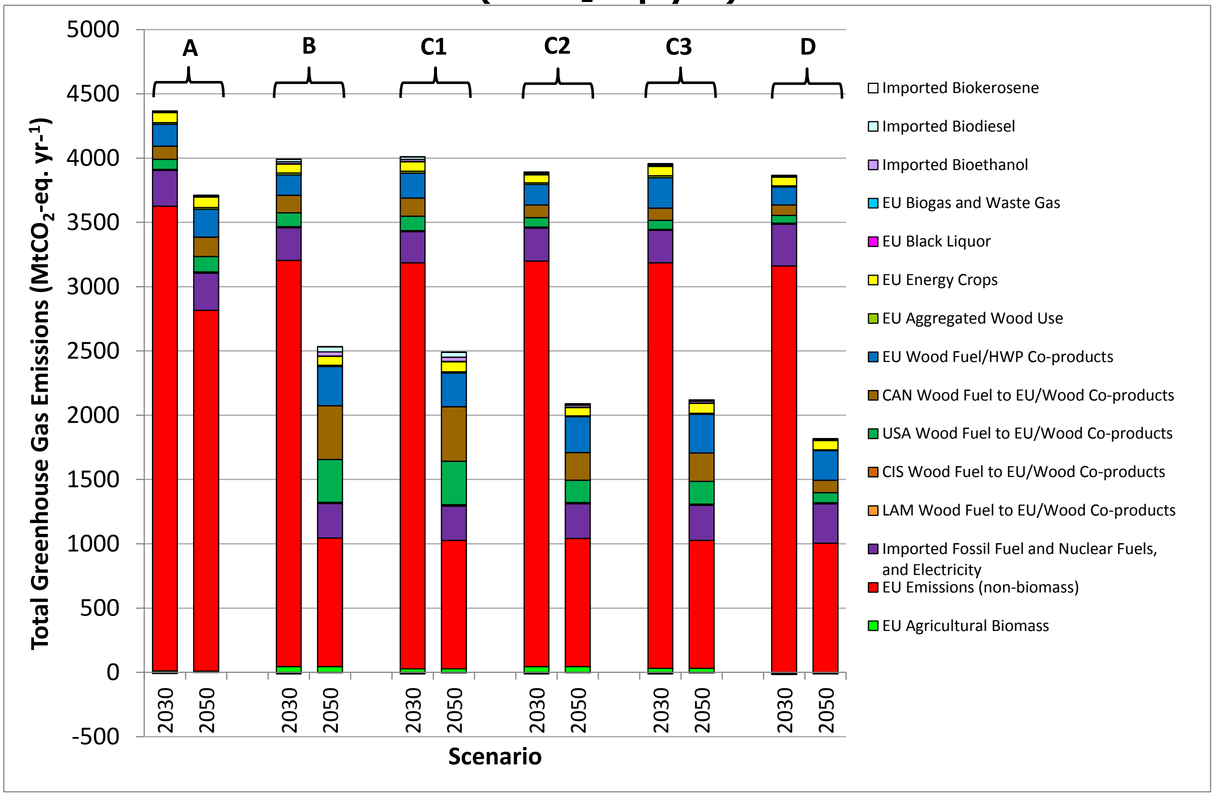
Notes to Table 3:

1 Fossil' (essentially the GHG emissions reported as "EU emissions (non-biomass)" in Figure 1)
2 'Bioenergy' (consisting of the sum of key contributions associated with bioenergy sources, specifically, the categories, "Agricultural biomass", "Energy crops" and the various categories of "Wood Fuel/Wood Co-products")
3 'Other' (consisting of the sum of contributions for all other categories, notably "Imported Fossil Fuel and Nuclear Fuels, and Electricity").

However, a key reason for the negligible change in 'Bioenergy' GHG emissions in Scenario C2 is due to the projected level of forest bioenergy use in 2030 being almost the same in Reference Scenario A and Scenario C2, whilst the level of forest bioenergy use in 2030 is higher in the other 'Carry on' Scenarios.

For all the decarbonisation scenarios, changes in GHG emissions relative to Reference Scenario A in the category 'Other' are smaller than for the 'Fossil' and 'Bioenergy' categories. However, a small but significant increase in 'Other' GHG emissions may be noted for Scenario D ('Back off'). This is mainly the result of increased emissions relative to Reference Scenario A in the detailed category of "Imported Fossil Fuel and Nuclear Fuels, and Electricity" (see Figure 2).

Figure 2 Total annual GHG emissions of different scenarios showing break-down by sources in 2030-2050 ($MtCO_2$-eq. yr^{-1})



Detailed analysis of contributions of bioenergy sources

This project has included a very detailed analysis and assessment of sources of GHG emissions due to various energy sources, particularly bioenergy sources.

Overall, under the high-bioenergy 'Carry on' Scenarios (compared with Scenario A), the net impact of bioenergy is a significant contribution towards the overall net GHG emissions savings achieved in 2030, alongside contributions due to other sources (carbon capture and storage, otherwise referred to as CCS, energy efficiency, nuclear and other renewable energy sources). In contrast, under the 'Back off' Scenario D, the reduced consumption of bioenergy, in general, leads to a net increase in its contribution to GHG emissions in 2030.

The contributions made by bioenergy towards net GHG emissions savings in 2030 are generally beneficial. However, as already indicated by the assessment based on Table 3, the detailed contributions are variable, depending on the scenario. The contribution of bioenergy towards GHG emissions savings is higher for scenarios emphasising bioenergy supply from domestic sources and lower for scenarios emphasising consumption of imported forest bioenergy and/or the relatively unconstrained use of bioenergy sources.

Notably, for Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood'), bioenergy makes a significant contribution towards overall reductions in GHG emissions in 2030. In contrast, under Scenario C1, which represents a situation in which the (relatively unconstrained) use of imported forest bioenergy is emphasised, bioenergy only makes a marginal contribution in 2030, with imported forest bioenergy sources in particular contributing a moderate net increase in GHG emissions.

The detailed analysis also indicates that additional measures to support positive forest management and wood use in terms of GHG emissions can have very strong positive impacts on GHG emissions reductions achieved through the use of bioenergy, notably forest bioenergy.

Levels of forest bioenergy use in 2030 are reasonably consistent with sustainable-yield supply, but beyond 2030 they can be challenging, with possible high associated GHG emissions

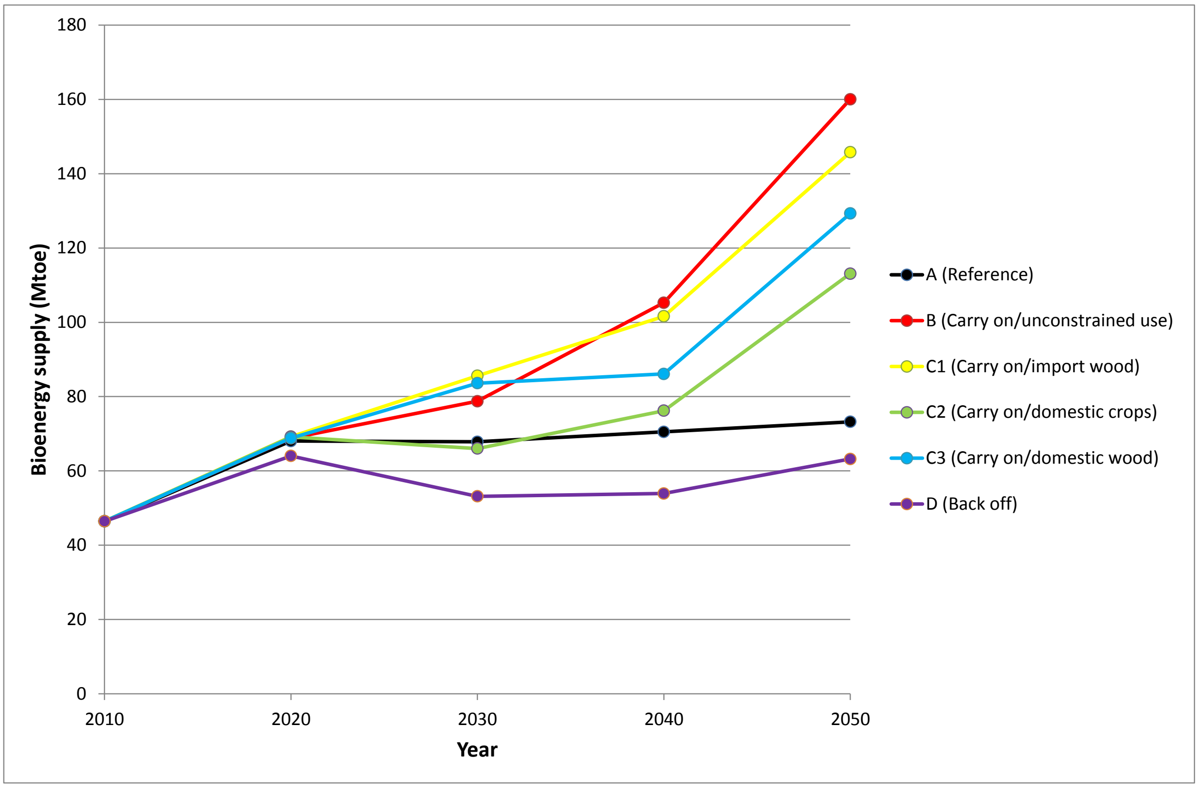
For the scenarios assessed, levels of agricultural biomass production for energy use within the EU27 region are consistent with the avoidance of significant risks of indirect land-use change (iLUC). Additionally, levels of forest biomass supply for use as energy, produced domestically within the EU27 region or supplied from elsewhere, are assessed as reasonably consistent with sustainable yield, depending on the levels of demand for forest biomass in other sectors and geographical regions.

However, as indicated in Figure 3, there is some evidence that higher levels of forest bioenergy supply in the high-bioenergy scenarios after 2030 present significant risks to sustainable-yield supply, particularly in the EU region, but also with notable impacts in other regions, particularly the USA. Hence, this is likely to involve very significant risks to achieving sustainable-yield wood supply, and would require significant changes in the capacity of the forestry sector.

Estimates for the sustainable-yield long-term potential total supply of biomass from forests have been proposed in this project, based on 70% of modelled estimates of theoretical long-term maximum total (above-ground) biomass production. Relevant estimates for the EU27 region, Canada and the USA are 314, 703 and 385 Modt yr^{-1} respectively (roughly 140, 310 and 170 Mtoe yr^{-1} primary energy supply).

The pronounced increases in the levels of forest bioenergy consumption (and therefore supply) from some point after 2030 up to 2050, as represented in the high-bioenergy scenarios, lead to net increases in total GHG emissions associated with the supply of forest bioenergy, for most sources (see results for 2050 in Figure 2).

Figure 3 Total forest bioenergy supply to the EU in 2010-2050 (Mtoe)



Towards a systematic qualitative assessment of sources of forest bioenergy

The assessment made in this project has confirmed that bioenergy sources are variable in terms of associated GHG emissions, but it is possible to identify systematic causes of this variability. This suggests the possibility of screening sources of bioenergy for high, moderate or low risk with regard to GHG emissions. However, it is challenging to devise a simple approach to this, for example by ranking different types of bioenergy feedstock according to their associated GHG emissions, because so many factors are involved. A more tractable approach involves the application of a **decision tree**, and a provisional version for application to forest bioenergy sources has been provided in this project.

As part of managing risk associated with increased consumption of bioenergy, a conclusion reached in this project suggest that proponents of significant new bioenergy projects (perhaps on the scale of several tens of megawatts) in the EU should demonstrate that genuine and significant GHG emissions reductions would be achieved, when GHG emissions due to biogenic carbon are considered. This would require *strategic assessment* of the impacts on total GHG emissions of commercial decisions involving major changes in activities that will lead to increased consumption of forest bioenergy, in principle similar to the assessment of policies.

Supporting positive approaches to forest management and wood use

If additional measures that support the use of forest bioenergy with low associated GHG emissions can be explicitly linked to activities aimed at increasing the production of forest bioenergy, then substantive reductions in total GHG emissions can be achieved.

Such measures could include efforts towards the positive management of vegetation carbon balances, as part of initiatives aimed at increasing the supply/consumption of bioenergy. For example, in the case of forest bioenergy, these might include situations in which rotations applied to forest stands are extended as part of optimising biomass productivity, or the growing stock of existing degraded or relatively unproductive forests is enriched to enhance carbon stocks and productive potential. It is also possible to create new forest areas with the specific purpose of managing them for wood production, provided that carbon stocks on the land are increased as part of the conversion of non-forest land to forest stands, and that there are no associated detrimental indirect land-use changes.

Other measures could involve favouring the co-production of forest bioenergy in conjunction with additional material wood products, targeting the displacement of GHG-intensive counterfactual products, and encouraging the disposal of wood products at end of life with low impacts on GHG emissions. Such types of supporting measure may be easier to encourage where the land areas involved and the biomass production are taking place within the EU region. However, extension to other regions may be possible if explicitly linked to requirements placed on EU consumers of bioenergy.

It is difficult to construct a simple list of “do’s and don’ts” for forest management and wood use, just as it is difficult to specify ‘low-risk’ and ‘high-risk’ types of wood feedstock for use as bioenergy, in terms of GHG emissions. However, one possible approach to cataloguing positive (and indeed negative) approaches to forest management and wood use for the supply of forest bioenergy might involve subsequent analysis of a decision tree such as proposed in this report. The analysis would be based on tracing the low-risk (and moderate/high-risk) bioenergy pathways in the decision tree, then, based on the outcomes, specifying a set of (possibly ranked) options for positive/negative forest management and wood use, characterising good and bad practice, in the form of clear and generally applicable practical prescriptions. A very tentative and preliminary version of such an analysis has been undertaken in this project.

The types of supporting approaches outlined above could be applied to demonstrate compliance with sustainability criteria attached to sources of biomass used for energy. This would not constitute a completely new approach to sustainability criteria for biomass, and would not operate in isolation. Rather, criteria derived from the measures considered above would complement existing sustainability criteria already referred to in the biomass energy, agriculture and timber sectors, which in some cases are already well developed and numerous.

How the quantitative assessment was carried out

Approach to life cycle assessment

The quantitative assessment of this project has been undertaken by applying consequential LCA, including defining a project objective, translated into an LCA "question" or goal that specified both the spatial and temporal systems boundaries of the study, as well as the nature and extent of process chains involved in the production and consumption of energy. Although the starting point of the study is the set of scenarios for possible policies for future energy consumption within the EU, in order to address this goal, it was necessary to account for subsequent prominent GHG emissions, both within the EU and outside the EU, due to the provision of imports of energy, including bioenergy, over a given period of time. Additionally, it was necessary to capture the changes in GHG emissions associated with bioenergy displacing non-biomass energy and, where appropriate, non-energy products, referred to, generally, as "counterfactuals".

The ultimate aim of this project has been to produce final quantitative results that consist of estimated total annual GHG emissions for the EU27 region under the six defined scenarios for biomass consumption, for the period between 2010 and 2050. The derivation of these estimated GHG emissions was achieved using the intermediate outputs of this project, produced through the application of the VTT-TIAM model, the CARBINE model, the MITERRA-Europe model and bespoke pathway workbooks. All these outputs were brought together in a consistent and interrelated manner.

Approach to modelling of scenarios

A complex approach to the modelling of scenarios in this project was necessary in order to assess, quantitatively, the potential role of bioenergy sources in contributing to future energy supply in the EU. Hence, it was a requirement of the project that the scenarios for future bioenergy consumption in the EU were developed in relation to existing scenarios for total primary energy use, namely, the PRIMES scenarios, produced for the European Commission in 2013. These scenarios were pertinent because they were referred to in the impact assessment of the communication on the policy framework for climate and energy in the period from 2020 up to 2030.

The PRIMES reference 2013 scenario was referred to in the development of the Reference Scenario A in this project. The EEMRES30 decarbonisation scenario was referred to in developing the various decarbonisation scenarios (40% GHG reduction target and 30% renewable energy target), representing either increased or decreased emphasis on bioenergy consumption after 2020.

Quantitative assessment required the estimation of the total GHG emissions associated with:

- The combustion of fossil fuels and releases from prominent industrial and agricultural activities within the EU
- The provision of fossil and nuclear fuels, and electricity imports into the EU
- Specifically, the changes in carbon sequestration and biogenic carbon emissions in forests and agricultural systems, and the indirect GHG emissions of bioenergy supply within and outside the EU.

The initial stage of this assessment was performed by simulating primary energy supply in the EU27 region between 2010 and 2050 with the VTT-TIAM model, for each of the scenarios defined in this project. To achieve this, for each scenario, the VTT-TIAM model was used to simulate changes in the consumption, not only of bioenergy sources, but also other relevant energy sources, including other renewable energy sources, nuclear power and fossil fuel sources. In addition, VTT-TIAM simulated changes in the technologies deployed as part of energy conversion, as well as measures aimed at achieving energy efficiency. Absolute total GHG emissions associated with all these changes in the use of energy were also simulated by the VTT-TIAM model, along with certain measures aimed at mitigation of GHG emissions, notably CCS. The estimates for GHG emissions produced as outputs by the VTT-TIAM model were supplemented by additional modelling for bioenergy sources, and for certain other energy sources not fully represented in the VTT-TIAM model.

The additional modelling required for bioenergy sources involved the quantitative assessment of GHG emissions associated with the consumption of bioenergy in the EU, including:

- Changes in carbon sequestration (increases or decreases over time) on agricultural land and in forest areas, due to the production of additional bioenergy
- Biogenic carbon emissions and indirect GHG emissions due to the combustion of the bioenergy
- Changes in GHG emissions (increases or decreases) due to the diversion of certain agricultural biomass sources from non-energy uses to use as bioenergy
- Changes in GHG emissions (increases or decreases) due to the diversion of wood from use for material wood products, to use instead as forest bioenergy, including impacts on GHG emissions occurring when materials are disposed of at end of life
- Changes in GHG emissions (increases or decreases) due to any co-production of additional material wood products in conjunction with the supply of the additional

forest bioenergy, including the displacement of counterfactual materials and impacts on GHG emissions occurring when materials are disposed of at end of life.

These GHG emissions were assessed through application of the MITERRA-Europe model (for agricultural biomass sources) and the CARBINE model (for forest biomass sources), and by developing bespoke pathway workbooks.

Key assumptions and criteria in development of scenarios

The development of the scenarios involved a number of key assumptions and criteria, as summarised in Table 4. Many of these derive from the underlying PRIMES scenarios (see earlier).

Table 4 Summary of key assumptions and criteria

Assumption/ criterion	Scenario type		
	Reference (A)	Carry on	Back off (D)
Underlying PRIMES scenario	Reference	EEMRES30	
Renewable energy target 2020/2030	20%/20%	20%/30%	
GHG reduction target/ level[1,2] 2020/2030/2050	20%/~30%/-	20%/40%/80%	
ETS carbon price 2020/2030/2050	€10/€35/€100	€10/€10.8/€152	
GHG savings criteria[2]	60% for biofuels	60% for all solid and gaseous biomass pathways as well as biofuels	
Scenario storyline details	No further developments beyond existing 2020 policies.	Measures to stimulate bioenergy demand and production.	Reduced contribution from bioenergy after 2020, so that the contribution of bioenergy is lower than in the Reference scenario after 2020.
Other constraints	No further developments beyond existing 2020 policies.	All biomass of agricultural origin consumed for heat and/or power generation in the EU region would also be produced in the EU region. Apart from Scenario B: • Strict GHG emissions mitigation criteria (e.g. see earlier), also • Encouragement of energy crops whilst avoiding iLUC • Application of sustainability criteria to forest biomass.	

Notes to Table 4:

1 These are GHG emissions reduction targets or levels, relative to 1990 levels, assumed in the PRIMES scenario referred to in constructing each scenario. The GHG emissions reduction level has a strong influence on the selection of renewable energy technologies (including bioenergy) in the modelling of scenarios.

2 In constructing each scenario, it was assumed that contributions to GHG emissions from bioenergy due to biogenic carbon were zero. The contributions to GHG emissions due to biogenic carbon were then assessed for all scenarios, along with other contributions to GHG emissions. This has been a fundamental research issue addressed by this project.

The storyline details in Table 4 for the high-bioenergy 'Carry on' scenarios refer to measures to stimulate bioenergy demand and production. Specifically, the modelling of these scenarios has suggested that high-bioenergy scenarios would require:

- Acceleration of the time to market of highly efficient bioenergy technologies
- Making decentralised and small-scale clean biomass conversion technologies more attractive
- Phasing out conventional biofuel production based on food crops after 2020, and replacement by waste and residue-based advanced biofuels
- Stimulation measures to make biogas technologies more efficient, including obligations to use waste heat, and further deployment of local residual biomass resources.

In contrast, Scenario D ('Back off') involves a reduced contribution from bioenergy after 2020, whilst also trying to achieve significant reductions in GHG emissions. The modelling of this scenario has suggested this would involve:

- The phasing out of large scale biomass technologies and no large-scale import of biomass
- The increased use of other renewable energy sources (particularly solar and wind power)
- More concerted efforts towards energy efficiency in the EU region, notably in the residential and transport sectors
- Increased use of nuclear power
- Some increased deployment of CCS technologies
- Increased reliance on natural gas, nuclear fuels and electricity imported into the EU region from elsewhere.

The logistical changes involved in all the decarbonisation scenarios are challenging and imply the incurring of costs. The costs incurred *specifically in the energy system* have been quantified in this project and are quite significant, particularly in the case of Scenario D (see previous discussion of cost performance of scenarios). It is important to note that the assessment of costs associated with the scenarios developed in this project, whilst consistent, is not comprehensive. For example, cost impacts in the wider wood industries (either positive or negative), due to changes in the use of forest biomass for energy, have not been assessed.

It is apparent from the preceding discussion that the development of scenarios for bioenergy use in the EU, linked to underlying PRIMES scenarios, required a holistic approach to the quantitative assessment of the scenarios developed in this project. This involved the assessment of changes in the energy system in relation to energy sources and conversion technologies associated with each of the scenarios. As a consequence, the GHG impacts assessed in this project reflect the contributions of many changes in the energy system, alongside contributions made by bioenergy sources.

Sensitivity analysis

The sensitivity of results to assumptions and choices amongst parameter estimates was explored systematically at several stages of the quantitative assessment.

Firstly, for each of the scenarios for bioenergy supply developed in this project, the forest modelling exercise explored how forest bioenergy supply, co-production of material products, and consequent impacts on forest carbon stocks and GHG emissions, might depend on approaches taken to forest management and wood use. In reality, the changes involved in forest management and wood use are likely to be multiple and complex, as has been discussed in the Task 1 report for this project. Accordingly, two contrasting possible approaches to forest management and wood use were developed, referred to as the ‘Precautionary’ approach and the ‘Synergistic’ approach.

For the definition of the ‘Precautionary’ approach to forest management and wood use, it was considered important not to make unduly optimistic or pessimistic assumptions about the types of forest and wood feedstock involved in the supply of forest biomass for energy to the EU. Hence, the approach was designed to represent a plausible set of changes in forest management and wood use to supply increased quantities of forest bioenergy in the EU in the absence of additional supporting policies and measures, or market-driven positive actions, which may aim to conserve or enhance forest carbon stocks alongside harvesting for bioenergy.

The ‘Synergistic’ approach was designed to represent a situation in which additional policies or measures (either market-driven or through regulation) may be taken that actively support the production of forest bioenergy with negative, relatively low or moderate risks of significant associated GHG emissions. The definition of the ‘Precautionary’ and ‘Synergistic’ approaches to forest management and wood use also considered sensitivities to different assumptions about the supply of forest bioenergy to the EU from external regions.

A further stage of sensitivity analysis involved considering the sensitivity of final results, notably with respect to assumptions choices concerning:

- Indirect GHG emissions factors associated with biomass processing, including the conversion of biomass into useful energy and any associated use of biomass co-products for materials or other products
- Counterfactuals for non-energy biomass products, notably material wood products, and their associated indirect GHG emissions factors (this was necessary because the increased use of biomass for bioenergy could lead to the diversion of the use of biomass for materials or animal feeds, or could involve increased co-production of non-energy products, depending on the details of the scenario being considered).
- Indirect GHG emissions factors for the disposal of biomass co-products at end of life.

The functionality of the calculation workbooks used for estimating indirect GHG emissions factors and the final project results was devised so that each pathway worksheet could be used to produce a range of results, consisting of low and high values, which would reflect reasonable variations of estimated GHG emissions for a given pathway for a specified year and location either within or outside the EU27 region. It should be noted that subsequent ranges are not intended to represent extreme low (absolute minimum) and extreme high (absolute maximum) values of results. Instead, they are intended to reflect typical variations that might be encountered under reasonably varying circumstances. These low and high values are used, in combination with the outputs of the VTT-TIAM, MITERRA and CARBINE models, to produce average results and associated ranges for the final results from this project for each specified scenario.

A final stage of sensitivity analysis was also conducted as part of the further investigation of the estimated net differences in GHG emissions specifically associated with the consumption of forest bioenergy. In particular, the sensitivity was explored of results with respect to total GHG emissions factors for a range of fossil fuels.

Limitations of this assessment

Like any such study, this project and its conclusions are subject to certain unavoidable limitations and uncertainties, including:

- The scenarios are not designed to predict an outcome for a 'most likely' future development of energy use in the EU
- The scenarios represent a small selection out of many possibilities
- There are limitations in the scenario modelling approach
- There are difficulties in determining the 'most likely' responses in forest management and wood use
- The scenarios only represent cases in which iLUC can be avoided
- There are inevitable uncertainties in consequential LCA studies, most notably related to the choice of counterfactuals
- There are some limitations in GHG emissions factors used in LCA calculations
- This assessment is restricted principally to the consideration of GHG emissions (i.e. other factors relevant to the assessment of the sustainability of bioenergy sources were out of scope)
- The final project results cannot be simply interpreted to determine the implications of the scenarios, in terms of the capacity of individual EU Member States, to meet EU domestic and international commitments for GHG emissions reductions.

1. Introduction

This report has been prepared towards fulfilment of a European Commission project, ENER/C1/427-2012 on 'Carbon impacts of biomass consumed in the EU'. The principal objective of this project, as stated originally in the project tender specification, is to deliver a qualitative and quantitative assessment of the direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios focussing on the period to 2030, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions.

1.1. Motivation for project

One of the main foundations of European Union (EU) energy policy is the need to reduce GHG emissions in a relatively short period of time to avoid the more extreme consequences of global climate change. The policy has emphasised the important role of renewable energy in general. Within this context, the extensive use of solid and gaseous biomass, particularly for heating, cooling and electricity generation, is regarded as an essential component of the policy[1]. This has been translated into EU Member State (MS) Action Plans[2] as part of the implementation of the European Commission's Renewable Energy Directive[3], which requires increasing the share of renewable energy to 20% of EU final energy consumption by 2020. A potential attraction and subsequent challenge for widespread utilisation of biomass is based on the diversity of their possible sources of supply, both within and from outside the EU, and the range of different technologies that can be used to provide reliable delivered energy, in suitable forms, to end users as realistic alternatives to fossil fuels.

There are other considerations which will determine whether greater reliance on biomass by the EU will deliver actual reductions in overall GHG emissions. Based on accumulating scientific and technical evidence and popular publications since the 1970s up until quite recently, the benefits and potential contribution of bioenergy as a renewable energy source with low emissions has seemed assured, with the claim occasionally being made that bioenergy was 'carbon-neutral'. However, a number of commentators and some

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[1] 'Communication from the Commission to the Council and the European Parliament: Renewable Energy Road Map: Renewable Energies in the 21st Century: Building a More Sustainable Future' COM (2006) 848 Final, Commission of the European Communities, Brussels, Belgium, 10 January 2007, http://ec.europa.eu/energy.

[2] 'Technical Assessment of Renewable Energy Action Plans' by M Szabó, A. Jäger-Waldau, F. Monforti-Ferrario, N. Scarlat, H. Bloem, M. Quicheron, T. Huld and H. Ossenbrink, Report EUR 24926, European Commission Joint Research Centre, Ispra, Italy, 2011, http://iet.ec.europa.eu/.

[3] 'Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC' European Commission, Brussels, Belgium, 5 June 2009, http://ec.europa.eu/energy.

scientific research results have queried the credentials of bioenergy and this has instigated a significant debate about the appropriateness of policies aimed at increasing the use of bioenergy as part of a strategy to meet requirements for energy and reduce GHG emissions. These generally negative commentaries on bioenergy invariably raise one or more of three key points of contention:

1. The use of forest biomass (harvested wood) as a source of bioenergy incurs a 'carbon debt' because the carbon emitted when harvested wood is combusted to produce energy may not be compensated for by the sequestration of carbon in forests. This is very likely to be the case if the additional harvesting of wood for use as bioenergy has a long-term negative impact on forest carbon stocks and sequestration (i.e. trees, litter or soil) and their development over time.
2. The use of harvested wood as a source of energy diverts some wood from more conventional use as a material (e.g. sawn timber and wood-based panel products), potentially requiring the use of alternative non-wood materials to manufacture these products, generally with high GHG emissions.
3. The use of agricultural land to grow bioenergy crops instead of food leads to requirements for food being met by intensifying agricultural production on other land elsewhere (within or outside the EU), with deleterious consequences for the carbon stocks on the affected land. This phenomenon is frequently referred to as Indirect Land Use Change or iLUC. (Issues concerning iLUC are also sometimes raised with regard to forest management for bioenergy production.)

The conflicting analyses and statements, either supporting or questioning the use of bioenergy, have caused some stakeholders to conclude that the carbon and GHG impacts of bioenergy production and consumption are 'complex and uncertain', and doubt has been cast on the potential role of bioenergy as part of low-GHG emissions energy policies. In order to make further progress on the development and implementation of policy regarding bioenergy and its potential roles in energy supply and climate change mitigation, it is essential to establish a sound expectation of future changes in GHG emissions (reductions or otherwise) associated with bioenergy production and consumption within the EU, taking full account of the carbon and GHG impacts of bioenergy use. As a fundamental starting point, an understanding is required of current research and the existing debate over 'carbon debt', iLUC and other displacement effects. In addition, relevant new insights need to be identified based on sound evidence. Proper determination of the carbon and GHG impacts of biomass energy consumed in the EU relies on a comprehensive, coherent and integrated approach. Ultimately, a thorough qualitative and quantitative assessment is required of the direct and indirect GHG emissions associated with the use of different biomass sources and bioenergy technologies under a number of scenarios for the nearer-term (2030) and longer-term (2050).

1.2. Objectives of project and tasks

1.2.1. Project objectives

Following from the motivation for this project, the principal objective of this project (European Commission, 2012) has been to deliver a qualitative and quantitative assessment of the direct and indirect GHG emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios, in order to provide objective information on which to base further development of policy on the role of bioenergy as a source of energy with low associated GHG emissions. The assessment has needed to address:

- Impacts on carbon sequestration and biogenic carbon emissions arising from using forest biomass
- Impacts of using land for energy crops
- Indirect land use change (iLUC)
- Other indirect impacts of diverting woody biomass to energy from other uses
- The full biomass/bioenergy life cycle and key GHGs
- Carbon and GHG impacts by 2030, with indicative projections to 2050 and over time horizons of 20, 50 and 100 years.

Assessments have involved comparison with a ‘Reference’ scenario in which biomass consumption for energy remains at levels attained in 2020, consistent with existing policies in the EU.

The qualitative and quantitative assessments have also aimed to deliver a set of selected key examples of calculations, with supporting explanation, to illustrate:

- The magnitudes of the impacts on vegetation and soil carbon stocks and indirect GHG emissions caused by management of forests and agricultural land for the production and use of bioenergy
- Sensitivities in quantified carbon and GHG impacts (e.g. due to type of land or crop involved or approach to management)
- How quantitative results for carbon and GHG impacts can vary, depending on the detailed approach taken to LCA and the assessment of biogenic carbon emissions.

In addition the qualitative assessment has aimed to deliver a clear description and explanation of:

- The essential processes (biological, physical, technical and socio-economic) involved in determining the carbon and GHG impacts of bioenergy production and use
- How decisions about the management of vegetation (forests and agricultural crops) and utilisation of harvested biomass can have impacts on these processes and cause changes in carbon stocks, carbon sequestration and GHG emissions
- The implications for the reliable assessment of carbon and GHG impacts of bioenergy use

- To the extent possible, the implications for the effective management of forests and agricultural land and conversion of biomass to energy, in order to meet energy needs in the EU with low GHG emissions.

The principal focus of the project has not been to produce a theoretical treatise on the GHG emissions associated with bioenergy use, or how to calculate them, but on a rigorous and robust assessment the carbon and GHG impacts of scenarios for future biomass use within the EU.

1.2.2. Formal statement of project purpose and LCA goal

A formal statement of the project purpose and LCA goal is considered critically important, particularly for the quantitative assessment undertaken in this project. The Task 1 report for this project (Matthews *et al*., 2014a), which presented the qualitative assessment, concluded that life cycle assessment (LCA) is the appropriate methodology for the assessment for GHG emissions associated with the consumption of bioenergy. However, LCA studies can address quite wide ranging goals, scopes and research questions. The specific methodological approaches and detailed calculation methods depend strongly on the specific goal, scope and question being addressed. As a consequence, the results of different LCA studies can vary considerably. The validity of the methodology and results of an LCA study therefore depend critically on a clear and accurate understanding of the purpose and goal.

The formal statement of the project purpose and objective (European Commission, 2012) has already been stated in Section 1.2.1. Given the particular focus on bioenergy, the study was required to cover, specifically:

- Changes in carbon stocks (trees, litter and soil) and sequestration in forests, arising from the use of forest biomass.
- Changes in carbon stocks and sequestration on agricultural land, due to the use of agricultural biomass
- iLUC impacts associated with energy crop production
- Other indirect imports associated with interactions between the use of wood for energy and non-energy applications (i.e. diversion and/or co-production)
- The full life cycle GHG emissions, both “direct” and “indirect” of relevant bioenergy process chains.

The objective was elaborated further by establishing that the quantitative assessment should determine “carbon impacts by 2030, with indicative projections to 2050”.

In the context of this required quantitative assessment, the project objective has been translated into the LCA goal, which was stated as:

To quantify the global emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources, resulting from implementation of possible EU policies, represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050.

This goal specifies both the spatial and temporal systems boundaries of the study, as well as the nature and extent of process chains involved in the production and consumption of energy. Although the starting point of the study is the possible policies for future energy consumption within the EU, in order to address this goal, it is necessary to account for subsequent prominent GHG emissions, both within the EU and outside the EU, due to the provision of imports of energy, including bioenergy, over a given period of time. Additionally, it is necessary to capture the changes in GHG emissions associated with bioenergy displacing non-biomass energy and, where appropriate, non-energy products, referred to, generally, as "counterfactuals".

1.2.3. Project tasks

The research approach has consisted of 4 research tasks:

- Task 1: Literature review of biogenic carbon accounting of biomass
- Task 2: Scenarios for biomass use in EU
- Task 3: Biogenic carbon emissions of biomass used in EU
- Task 4: Assessment of indirect emissions from different sources of solid biomass.

The effective assessment of carbon and GHG impacts of bioenergy consumed in the EU has also required the integration of existing models and relevant modelling capabilities. Therefore, an additional cross-cutting task has been concerned with integration of modelling and calculations.

1.3. Structure of this main final project report (Part A)

This document constitutes Part A of the final project report. It is the main part of the final project report, consisting of a summary description of the qualitative assessment of Task 1, and a full description of the quantitative assessment undertaken in Tasks 2 to 4.

The literature review of biogenic carbon accounting of biomass, undertaken in Task 1 of this project, has already been the subject of a substantial report (Matthews *et al.,* 2014a). Readers are referred to that report for full information on the outcome of Task 1. However, a summary report on Task 1 is provided in Section 2 of this final project report, in which the conclusions are also further elaborated (see Section 2.4).

Section 3 of this final project report describes the work and results of Task 2, which developed scenarios for biomass use in the EU, taking into account types of biomass sources (inside and outside the EU) and relevant bioenergy technologies that are available now and are likely to be used in the future.

Work undertaken on Task 3 of this project, for the assessment of GHG emissions due to biogenic carbon of biomass consumed for energy, is described in Section 4 of this report. The essential results of Task 3 are estimates of the biogenic carbon emissions associated with the Task 2 scenarios for bioenergy consumption.

Section 5 of this report describes the work of Task 4, to determine GHG emissions that have not been addressed elsewhere in this quantitative assessment of the carbon impacts of different scenarios, mainly involving indirect GHG emissions.

The integration of the various results developed in Tasks 2 to 4 of this project, to produce final estimates of the carbon impacts of specified scenarios for biomass use for energy in the EU, is described in Section 6. The final results of this project are also presented and discussed in this section.

Section 7 summarises key conclusions, and considers implications for bioenergy use, drawing on the quantitative assessment undertaken in Tasks 2 to 4 of this project, and also on the qualitative assessment already reported based on Task 1 (Matthews *et al.*, 2014a).

1.3.1. Supporting information in appendices (Part B)

The quantitative assessment presented in this report has involved considerable underlying, detailed analysis, and the collation and processing of relevant datasets. Much of this detail is unsuitable for discussion as part of this main final project report. However, as a contribution towards transparency in calculations, and data referred to, in producing this quantitative assessment, further detailed information is provided in a set of appendices to this main report.

The quantitative assessment has also involved the application of several complex models, in the development of the scenarios for energy use by the EU, and in the subsequent estimation of impacts on terrestrial carbon stocks and capacity for carbon sequestration. It is very difficult to provide full transparency for the calculations made by these models. To address this, several supporting appendices provide descriptions of relevant models, or simplified worked examples to illustrate how the models derive their output results, depending on input data and assumptions.

All of these appendices are included in a separate document, constituting Part B of this final project report. Cross references to the appendices are made at appropriate points throughout the discussion in this main final project report.

1.4. Representation of countries and regions in scenarios

As explained in Section 3.3.2, which introduces the storylines for the scenarios that have been developed, for the purposes of this project, it was assumed that all biomass of agricultural origin consumed for heat and/or power generation in the EU region would also be produced in the EU region. However, the different scenarios for biomass consumption and supply developed in Task 2 explicitly recognised that forest biomass could be produced within the EU region and also imported from other countries. It was, therefore, necessary to represent the potential contributions due to forestry in a wide range of relevant regions and countries.

Although the focus of this project is on the consumption of solid and gaseous biomass used in electricity and heating/cooling in the EU, in order to ensure that the assessment to be sufficiently comprehensive (see Section 1.2.2), as part of the development of scenarios, it was also necessary to consider contributions to EU energy supply due to biofuels. The supply of biofuels, as represented in the scenarios, has involved a number of countries and regions outside the EU region.

Table 1.1 shows how the countries of key regions potentially supplying the EU with biomass and biofuels have been represented in the modelling of scenarios.

Table 1.1 Representation of countries in regions supplying forest bioenergy to the EU

Region	Representation
EU27	Agriculture, agricultural biomass production, forests, forest management and wood production in each EU27 Member State was modelled individually. For forestry, Cyprus and Malta were excluded due to their small forest areas.
CIS	Forests, forest management and wood production was modelled individually for Belarus, European Russia (effectively west of the Urals) and Ukraine For biofuels, CIS refers more widely to the countries of the Commonwealth of Independent States (mainly former-Soviet Union).
CAN or Canada	Forests, forest management and wood production was modelled individually for six ecological zones represented in the Canadian National Forest Inventory
USA	Forests, forest management and wood production was modelled individually for each of the conterminous States of the USA
LAM	Forest bioenergy supplied from the LAM region was assumed to be restricted to production from purpose-grown plantation forests established on abandoned and degraded agricultural land in Brazil. Contributions from Brazil to forest bioenergy supply were not included in all scenarios. In the case of the supply of biofuels, LAM refers more widely to the countries of Central and South America.
ODA	Biofuels only. Asian countries referred to, collectively, as Other Developing Asia, including Indonesia and Malaysia.

1.5. Combined impacts of different greenhouse gases

In this report, to enable comparison, and to permit an appreciation of the combined impact of different GHGs, emissions of CH_4 and N_2O are expressed in units of equivalent CO_2. This is achieved by referring to quoted values of global warming potentials (GWPs) for these GHGs. The values referred to in this report for the GWP for the key GHGs are taken as 1 for CO_2, 25 for CH_4 and 298 for N_2O, hence 1 tonne of CH_4 equals 25 tonnes CO_2 equivalent (25 tCO_2-eq). These GWPs are based on modelling the relative warming potential of CO_2, CH_4 and N_2O over a 100-year time horizon, as reported in IPCC (2007). It should be noted that these GWP values are being adopted for use in the calculation of

GHG inventories reported to the UNFCCC and under the Kyoto Protocol, replacing earlier GWP values reported in IPCC (1996). The IPCC has further updated the values for GWPs in its Fifth Assessment Report, but these have not yet been adopted for use in the calculation of GHG inventories. Other studies referred to in this report may use different values to those adopted here for the GWPs for CH_4 and N_2O.

The report makes frequent reference to stocks of carbon in vegetation, litter and soil, and to carbon sequestration. A stock of 1 tonne carbon in vegetation, litter and/or soil is equivalent to 44/12 = 3.67 tonnes of sequestered CO_2.

2. Literature review of biogenic carbon accounting of biomass

2.1. Purpose

The purpose of this section is to provide a summary overview of the outcome of Task 1 of this project (Matthews *et al.*, 2014a), which was concerned with a review of scientific literature on the contributions of 'biogenic carbon' to GHG emissions due to the production and use of bioenergy, and how these contributions may be appropriately included in methodologies for calculating GHG emissions. The review was concerned primarily with woody biomass harvested from forests for use as bioenergy, referred to in this report as 'forest bioenergy', because this reflects an important current focus of debate in the scientific literature. The Task 1 report effectively constitutes the qualitative assessment required as part of the principal objective of this project, and is divided into five sections:

1. Introduction
2. Forests, forest management and wood utilisation
3. Forest biogenic carbon and its management
4. Life cycle assessment: essential concepts and key issues
5. Assessment of literature on GHG emissions of GHG bioenergy.

Detailed supporting information is provided in 11 appendices.

2.2. Approach to literature review

In order to set the context for the qualitative assessment of GHG emissions due to consumption of forest bioenergy in the EU, the Task 1 includes discussions of a number of salient underlying issues.

The Introduction section of the Task 1 report sets out the basis for the debate over the contributions to GHG emissions due to the consumption of forest bioenergy, and specifically due to biogenic carbon of biomass. On one side of the debate, a simple consideration of the intrinsic physical and chemical properties of forest bioenergy strongly indicates that its use is likely to involve high GHG emissions. Specifically, the actual quantity of carbon released when wood is combusted to produce a given unit of energy is typically greater than would be the case if fossil fuels, such as natural gas, oil or coal, were to be used. On the other side of the debate, it is recognised that the GHG emissions released from forest bioenergy can be compensated for by sequestration of carbon as part of the ongoing growth of forests. (Indeed, the 'biogenic carbon' of forest bioenergy has already been sequestered from the atmosphere as part of this process.) Hence, under certain circumstances, GHG emissions arising from the use of forest bioenergy can be regarded as negligible, or perhaps even negative. However, this is unlikely to be the case in situations where the scale of harvesting to produce forest bioenergy is significantly increased. It follows that, overall, the GHG emissions due to the consumption of forest bioenergy depend on an interplay between the biogenic carbon released when wood is harvested and combusted to produce energy, and the rate of sequestration of carbon in forests, prior to and subsequent to, any harvesting of wood. This implies a critical role for forest management. The Introduction section of the Task 1 report points out that these fundamental insights have long been identified and understood in the scientific literature. However, it is concluded that three key questions require further exploration:

1 Is it possible to discern any patterns in the results presented in the existing scientific literature and, in the process, establish whether there are any critical factors determining sensitivity of GHG emissions associated with forest bioenergy? Can such understanding be used to identify lower-risk forest bioenergy pathways in terms of GHG emissions?
2 To what extent are results for GHG emissions estimated for forest bioenergy sensitive to variations in calculation methodologies, and is it possible to understand variability in results in terms of differences in the detailed approaches to calculation adopted in different studies of forest bioenergy?
3 Is it possible to draw insights from the existing scientific literature to identify elements of methodology that would be appropriate for application as part of the assessment to be carried out in this project, including approaches for the reporting and presentation of results?

In order to explore and answer the above three research questions thoroughly, the systematic assessment of the scientific literature is complemented by critical discussion of the essential issues regarding forest bioenergy, associated GHG emissions, methods for their calculation, and the role of forest carbon stocks and forest management.

Accordingly, in order to set the context for the assessment of GHG emissions due to consumption of forest bioenergy in the EU, sections of the report cover:

- An explanation of the status of forests in the EU and more widely
- An overview of the role of forest carbon stocks as biogenic carbon in contributing to the GHG emissions of forest bioenergy
- A discussion of key concepts and issues concerning LCA methodology, with particular reference to inclusion of biogenic carbon in LCA calculations.

The key purposes of the review of the status of forests and current and potential future use of forest bioenergy in the EU are:

- To review how forests are currently managed
- To review how forest bioenergy is conventionally produced as part of forest management
- To assess how changes might occur in forest management and patterns of wood use to meet significantly increased demand for forest bioenergy in the EU.

The overview of the role of forest carbon stocks as biogenic carbon in contributing to the GHG emissions of forest bioenergy is intended to:

- Review current understanding of the dynamics of forest carbon stocks
- Consider the relative importance of forests as reservoirs of carbon and producers of wood
- Consider the relative importance of harvested wood as a source of energy and of materials and fibre, for potentially achieving GHG emissions reductions
- Assess how forest carbon stocks and wider GHG dynamics of wood production systems may respond to management interventions aimed at increasing production of forest bioenergy, and the implications for GHG emissions
- Distinguish as clearly as possible the factors associated with forest management and wood use that determine biogenic carbon dynamics associated with forest bioenergy, e.g. effectively as 'low risk', 'limited potential' or 'high risk'.

The discussion of key concepts and issues concerning LCA methodology aims to:

- Introduce the essential elements of LCA methods and calculations.
- In particular, to clarify why different LCA studies can, quite validly, produce different results.
- Establish the prime importance of determining a clear goal for any LCA study to address.

These three discussions in the Task 1 report, respectively, set out the essential background concerning:

- Forests, their management and the utilisation of wood for bioenergy and solid wood products
- Forest carbon stocks and carbon sequestration, forest management and the role of biogenic carbon
- Fundamental principles and practices of life cycle assessment.

These discussions effectively lay the ground for a critical review of existing literature on the GHG emissions associated with forest bioenergy and how these should be assessed. This critical review represents the main substance of the Task 1 report.

The Task 1 report is not the first to attempt a literature review and there are a number of important precedents which require careful consideration. The Task 1 report considers in detail a particularly prominent recently published review, the JRC technical report on carbon accounting for forest bioenergy (Agostini *et al.*, 2013). This provides a context in which to analyse other notable reviews and commentaries concerning scientific understanding of GHG emissions associated with forest bioenergy. Five such reviews and commentaries are considered. Wider consideration is then given to individual scientific studies of the GHG emissions of forest bioenergy, and an attempt is made to extend and elaborate on the insights drawn by the previous reviews and commentaries on the subject. Based on these qualitative assessments, the Task 1 report offers some concluding remarks and presents some key messages.

2.3. Findings

Based on the explanatory discussions of underlying issues, and the ensuing critical review, the Task 1 report arrives at a number of findings about the GHG emissions associated with forest bioenergy, and potential implications for the management of forests for production of bioenergy. A number of findings are also relevant to understanding appropriate approaches to the assessment of GHG emissions of forest bioenergy sources.

2.3.1. Careful examination of existing scientific literature suggests a consistent story

To sum up the assessment presented in Section 5 of the Task 1 report, a superficial consideration of the scientific literature on GHG emissions associated with forest bioenergy would most likely arrive at the impression that the outcomes and conclusions of different publications are highly variable and that the overall picture of forest bioenergy is confused and sometimes contradictory. However, on closer examination, it becomes evident that there is a certain level of fundamental agreement or at least consensus on some basic phenomena.

2.3.2. Biogenic carbon needs to be included in strategic assessments of GHG emissions arising from consumption of forest bioenergy

Fundamentally, it is undeniable that the status of forest bioenergy as an energy source with either low or high associated GHG emissions is inextricably linked to the property of wood as a reservoir of biogenic carbon and, crucially, how the source of that biogenic carbon, i.e. the carbon stocks in forests (in trees, litter and soil), is managed to produce bioenergy.

It is particularly important to allow for biogenic carbon when making strategic assessments of GHG emissions due to policies, plans or decisions involving changes in activities that will lead to increased consumption of forest bioenergy. It is important to clarify that what needs to be demonstrated is the achievement of significant reductions in GHG emissions, as the 'global consequence' of any changes to the management of forest areas involved in the supply of forest bioenergy, implying the application of consequential LCA for the purposes of assessment.

2.3.3. GHG emissions of forest bioenergy display systematic variation more than uncertainty

An analysis of published case studies indicates that forest bioenergy sources may involve widely varying outcomes in terms of impacts on GHG emissions. However, it is very important to stress that this variability does not imply that outcomes are uncertain. Rather, much of the variation is systematic and can be related to clearly identifiable factors.

2.3.4. Many factors can influence the GHG emissions of forest bioenergy

The variability in reported results for GHG emissions of forest bioenergy reflects many factors related to the forest bioenergy systems being studied and the methodologies applied in calculations. However, a meta-analysis of published studies would appear to indicate that a major reason why different studies have arrived at different results and conclusions is simply down to the fact that they have looked at different types of forest bioenergy source.

2.3.5. Results for GHG emissions also depend on the methodology applied for assessment

Results reported by published studies for GHG emissions of forest bioenergy also vary because different studies have used different methodologies, often because studies have different goals and address different research questions. For example, most studies apply methods consistent with consequential LCA, with the aim of assessing the impacts of decisions to increase consumption of certain types of forest bioenergy sources. However, a few studies apply attributional LCA as part of the 'operational' assessment of (typically absolute) GHG emissions of specific forest bioenergy sources. These two types of study will, inevitably, arrive at very different results for the GHG emissions of forest bioenergy sources. Clearly, only the former type of study is relevant to the assessment of the potential impacts of policies encouraging the consumption of forest bioenergy. At the same time, it should be stressed that such variations between studies are not necessarily shortcomings or substantive methodological conflicts. Rather, these variations reflect the large range of possible scenarios for forest bioenergy use that can be studied, and the diversity in the specific objectives and questions addressed by different studies.

2.3.6. Increased harvesting typically involves reductions in forest carbon stocks

There is widespread recognition in the research literature that increasing the levels of wood harvesting in existing forest areas will, in most cases, lead to reductions in the overall levels of forest carbon stocks (i.e. in trees, litter and soil) compared with the carbon stocks in the forests under previous levels of harvesting. Where the additional harvesting is used to supply bioenergy as the sole product, then such forest bioenergy will typically involve high associated GHG emissions (i.e. compared with fossil energy sources) for many decades.

2.3.7. Increased biomass production sometimes involves increased forest carbon stocks

There is also recognition that there exist some specific cases where forest management interventions to increase biomass production may involve increased forest carbon stocks. These include situations in which rotations applied to forest stands are extended as part of optimising biomass productivity, or the growing stock of existing degraded or relatively unproductive forests is enriched to enhance productive potential. It is also possible to create new forest areas with the specific purpose of managing them for wood production, provided that forest carbon stocks on the land are increased as part of the conversion of non-forest land to forest stands, and that there are no associated detrimental indirect land-use changes.

2.3.8. GHG emissions of forest bioenergy are very sensitive to assumptions

The outcomes of GHG assessments of forest bioenergy are very sensitive to the counterfactual scenario for land use. The projected development of forest carbon stocks under the counterfactual scenario will depend on the assumed forest management, the potential of the growing stock forming forest areas (tree species, age distribution, climatic conditions, soil quality, nutrient regime etc.), and on the likelihood of natural disturbances.

Similarly, outcomes are very sensitive to the counterfactual scenario for energy systems, which also involve assumptions which may be very uncertain, e.g. because of unforeseen market-mediated effects or future policy developments.

Uncertainties in counterfactual scenarios are inherent due to the fact that the counterfactual scenario is, by definition, a path that characteristically is not followed. It is thus never possible to verify what would have actually happened. Long time horizons related to forest carbon cycles and lifetimes of energy systems increase the inherent uncertainty. It follows that counterfactual scenarios need to be developed carefully and robustly, and assumptions must be transparent to ensure they are clearly understood when results are interpreted.

2.3.9. GHG emissions of forest bioenergy sources vary over time

The GHG emissions due to the use of forest bioenergy generally vary over time. As a consequence, different results are obtained for GHG emissions when calculated over different periods (or 'time horizons'), e.g. 1 year, 10 years or 100 years. This complicates the characterisation of forest bioenergy sources, particularly with regard to their potential to contribute to reductions in GHG emissions. There are many examples involving an initial period of increased GHG emissions, compared to the alternative of using fossil energy sources, followed eventually by reductions in GHG emissions. The initial period of increased GHG emissions can vary from less than one year to hundreds of years, depending on the type of forest bioenergy.

There is no obvious scientific basis for selecting a standard time horizon – essentially this is a politically-related decision. The choice of time horizon is thus a critical issue in the assessment of GHG emissions associated with the use of forest bioenergy. In the Task 1 report, a target year of 2050 was identified as a policy-relevant time horizon (Allen *et al.*, 2009; Meinshausen *et al.*, 2009).

2.3.10. Forest bioenergy sources likely to contribute to levels of consumption in 2030 vary in risk

A provisional qualitative assessment was made of the likelihood of particular forest bioenergy sources being involved in meeting levels of consumption in 2030. These various forest bioenergy sources varied from 'low risk' to 'very high risk', according to the likelihood of adverse impacts on GHG emissions reductions over the period to 2050, as illustrated in Table 2.1[4].

This implies that, potentially, increased consumption of forest bioenergy in the EU could make a highly significant contribution towards achieving reductions in GHG emissions, if 'low risk' and 'moderate risk' sources are used. Conversely, if 'high risk' or 'very high risk' sources are used, increased consumption of forest bioenergy could make a negligible contribution or could seriously frustrate the achievement of GHG emissions reductions.

It should be emphasised that the assessment in Table 2.1, based on analysis presented in the Task 1 report for this project, must be regarded as preliminary. Further progress towards a more definitive elaboration of the qualitative assessment undertaken for this project is described in Section 2.4.

As part of this qualitative assessment, it is difficult to clarify whether increased consumption of forest bioenergy in the EU is likely to be achieved through 'low risk' and 'moderate risk' scenarios for forest management and bioenergy production, such as increased extraction of harvest residues, or whether a wider range of scenarios with varying risk may be involved. A full systematic analytical assessment is required to determine whether scenarios are more or less likely to actually be involved in meeting increased demands for bioenergy, which is a subject for further research.

[4] It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 of the Task 1 report, where levels of risk are also defined in Table 5.2.

Table 2.1 Classification of forest management/bioenergy production scenarios in terms of risk

Risk[1]	Forest management/bioenergy production scenario	Comments
Scenarios potentially relevant to 2020 targets for bioenergy consumption		
'Very high' and 'high'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with low potential for displacement of GHG emissions associated with solid wood products[2].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[2].
	Salvage logging and restoration of forests on rotational management for production of bioenergy only[3].	
	Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged.	Very sensitive to counterfactuals for forest bioenergy and solid wood products.
'Moderate'	Salvage logging for co-production of solid wood products and bioenergy followed by restoration of forest areas with moderate harvesting intensity, also for co-production.	
	Extraction of harvest residues[4].	Sensitive to harvesting of stumps, and to fossil energy counterfactual.
	Extraction of pre-commercial thinnings.	Sensitive to fossil energy counterfactual.
'Moderate' to 'low'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with high potential to displace GHG emissions associated with solid wood products[2].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[2].

Notes to Table 2.1:

1 It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 of the Task 1 report, where levels of risk are defined in Table 5.2.

2 The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals (see for example Matthews *et al.*, 2014b).

3 High/very high risk has been assigned because of the specifics of the scenario considered in the original literature, i.e. conversion to rotational management for bioenergy production as part of restoration of forest, as opposed to a counterfactual of restoration to biologically mature forest with high carbon stocks.

4 Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.

Table 2.1 (continued) Classification of forest management/bioenergy production scenarios in terms of risk

Risk[5]	Forest management/bioenergy production scenario	Comments
Additional scenarios potentially relevant to bioenergy consumption above 2020 targets		
'Very high' and 'high'	Additional harvesting of stemwood and 'residual wood' for bioenergy only in forest stands for fire prevention.	
	Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	Sensitive to fossil energy counterfactual.
Scenarios unlikely to be involved in increased bioenergy consumption		
'Very high' and 'high'	Harvesting of forest with high carbon stocks and replacement with rotational forest management for production of bioenergy only.	
	Harvesting forests with high carbon stocks for bioenergy only, followed by restoration of forest areas with low productivity plantation for bioenergy only.	
'Moderate'	Harvesting of forest with high carbon stocks and replacement with high-productivity short rotation plantations for production of bioenergy only.	Sensitive to the assumption that short rotation plantations have much faster growth rates than previous forest
'Moderate' to 'low'	Diversion of harvested wood from solid wood products to bioenergy, combined with reduced harvesting intensity.	Requires reduced harvesting intensity to fully compensate for possible impacts of diverting wood
'Low'	Enrichment of growing stock in existing forest areas as part of enhancement of bioenergy production.	Important to avoid negative impacts on soil carbon stocks, where these could occur.
	Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock[6].	Sensitive to risks of iLUC.

Notes to Table 2.1:

5 It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 of the Task 1 report, where levels of risk are defined in Table 5.2.

6 It must be stressed that these activities have been classified as low risk on the assumption that risks of iLUC would be mitigated, e.g. by restricting the activities to marginal/low productivity agricultural land.

2.3.11. Low/high-risk cannot be determined simply in terms of feedstocks

The analysis of scientific literature suggests it is possible to identify 'low risk' and 'high risk' sources of forest bioenergy. However, the same feedstocks can be involved in 'low risk' and 'high risk' scenarios. As a consequence, it is not possible to limit or remove risk of adverse GHG emissions due to consumption of forest bioenergy by favouring particular feedstocks and discouraging the use of others.

In this context, it is also important to recognise that, as part of sustainable forest management and wood utilisation:

- Different types and sizes of trees and quantities of wood are harvested at different points in the cycle of forest management. Trees harvested at different ages (and hence of particular dimensions and physical characteristics) will be suitable for different applications and end uses.
- At any one time across a whole forest, a broad mix of trees will be harvested which will be variously suitable for a range of end uses, even though particular types of trees may be harvested from individual stands for specific uses, depending on their stage of development. Collectively, the broad mix of trees harvested from a forest meets a range of demands.
- The wood processing sector is complex, with outputs from the forest providing feedstocks for the manufacture of structural sawn timber, plywood, pallets and fence posts, particleboard and fibreboard, paper and other products including bioenergy.
- The complexity of the wood processing sector can present challenges when attempting to track flows of wood from the forest through to ultimate end use.

For these reasons, there are likely to be very serious obstacles to regulating the consumption of forest bioenergy based on individual consignments of forest bioenergy or based on specific types of forest bioenergy feedstock.

This conclusion could be viewed as a practical barrier to the effective deployment of forest bioenergy. However, the issues have been reviewed in subsequent developments of the project after the completion of Task 1, and an attempt has been made at further clarification (see Section 2.4 in this final project report).

2.3.12. There is reasonable consistency in outcomes for particular bioenergy sources

There is reasonable consistency in the research literature on outcomes for particular forest bioenergy sources with regard to impacts on GHG emissions. The meta-analyses of published studies by the JRC review, Lamers and Junginger (2013) and in the Task 1 report, list a number of specific examples of forest bioenergy sources, which can be categorised in terms of associated impacts on GHG emissions, as summarised in Table 2.1.

2.3.13. Significant initiatives involving increased consumption of forest bioenergy could be subjected to strategic assessment for impacts on GHG emissions

One possible step towards managing risk associated with increased consumption of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects (perhaps on the scale of several tens of megawatts) in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. This would require *strategic assessment* of the impacts on total GHG emissions of commercial decisions involving major changes in activities that will lead to increased consumption of forest bioenergy, in principle similar to the assessment of policies.

It must be stressed that such assessment of new activities involving consumption of forest bioenergy would be undertaken before a decision is taken to proceed with the activities. Such an approach is not suggested for ongoing monitoring of GHG emissions, for example at bioenergy installations to demonstrate compliance with regulations, such as targets for net GHG emissions savings. Further research is needed to assess the implications of the findings of this report for the development of robust methodologies for monitoring of GHG emissions for such regulatory purposes.

Some relatively recent developments with regard to such methodologies should be noted, in particular, the Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, proposed by the US EPA (EPA, 2014). As part of future work, there may be merit in evaluating the EPA methodology alongside a specific implementation of the more flexibly-defined approach suggested in the Task 1 report, perhaps through consideration of suitable case studies, actual or hypothetical.

2.3.14. Increased use of forest bioenergy might be integrated with carbon stock management

The possibilities could be considered for complementary approaches to support positive management of carbon stocks in forests, or more generally in terrestrial vegetation and soil. Such action would underpin a positive contribution by forest bioenergy to achieving reductions in GHG emissions. Ideally, any relevant mitigation actions would be explicitly linked to land use activities taking place as part of bioenergy production, although, at least in principle, the mitigation actions could also be taken independently of bioenergy production. In this context, it should be noted that an existing EU Decision on accounting for GHG emissions in the Land Use, Land-Use Change and Forestry sector effectively provides an appropriate accounting framework at national scale within the EU.

2.3.15. The suitability of metrics for GHG emissions depends on the question

Metrics used for assessing the potential of forest bioenergy need to be relevant to the goal, scope and policy or research question being addressed. For example, if there is interest in achieving a significant level of GHG emissions reductions, say 50% to 95%, by a target year such as 2020 or 2050, then results expressed as GHG emissions payback times may be useful for initially sifting out high risk scenarios for forest bioenergy consumption, but are not appropriate for assessing whether target levels of emissions reductions are likely to be met. In this context, a metric such as cumulative reduction in GHG emissions is more appropriate. Furthermore, if there is interest in understanding the effects of various scenarios for forest bioenergy consumption on cumulative radiative (climate) forcing, then a metric should be used which directly expresses such effects.

2.4. Elaboration and refinement of qualitative assessment

Following the completion of Task 1, some of the principles established as part of the qualitative assessment were elaborated and refined as part of the subsequent development of this project. The motivation for this arose from several conclusions arrived at in Task 1, as outlined in Section 2.3 of this final project report. Firstly, it was concluded that forest bioenergy sources likely to contribute to bioenergy consumption in 2030 vary in risk (Section 2.3.10). Stakeholders with interests and/or concerns regarding the use of forest bioenergy in the EU have been seeking a better understanding about what actions are appropriate to take to ensure that forest bioenergy consumed in the EU has low associated risk with respect to GHG emissions. Unfortunately, the Task 1 assessment also concluded that low and high risk sources of forest bioenergy cannot be determined simply in terms of forest biomass feedstocks (Section 2.3.11). Consequently, it was concluded that there are likely to be serious obstacles to regulating the consumption of forest bioenergy based on individual consignments of forest bioenergy, or based specific types of feedstock. However, a further conclusion of Task 1 was that significant initiatives involving increased supply and consumption of forest bioenergy could be subjected to strategic assessments of impacts on GHG emissions (Section 2.3.13). Specifically, it was suggested that one possible step towards managing risk associated with increased use of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. There has been some discussion of this possible approach amongst stakeholders. The presumption has been that any such strategic assessment would be quantitative, i.e. involving explicit estimation of the GHG emissions associated with a specified bioenergy project. In this respect, the details of the methodology to be applied for such assessments would not be prescribed in great detail, although key principles could be specified. The responsibility would be placed on the project proponents to identify and apply a methodology that was appropriate for the particular project being assessed, and to provide adequate supporting justification and transparent calculations. This approach may be worthy of further research and/or piloting.

In principle, strategic assessments of significant initiatives involving increased consumption and supply of forest bioenergy could also be qualitative. This could be achieved by analysing the approaches to forest management and the utilisation of harvested biomass, and classifying them in terms of risk. For example, such an approach could be useful for making preliminary screening assessments of forest bioenergy initiatives and projects. Any initiatives and projects clearly identified as high risk could be discounted at an early stage, whilst those passing the qualitative assessment could then be subjected to quantitative assessment. The qualitative assessment in Table 2.1 (see Section 2.3.10) was able to distinguish forest bioenergy sources in terms of risk, but these were defined in broad terms and represented isolated cases. Furthermore, the cases referred to in the assessment were often defined, implicitly, as arbitrary combinations of factors with respect to forest management and wood feedstocks, reflecting the specific cases considered in the scientific literature. As such, the assessment in Table 2.1 could not be described as systematic, and is difficult to interpret and apply in a wider context.

One possible way of permitting systematic qualitative assessment of initiatives involving increased consumption and supply of forest bioenergy could be to develop a decision tree. A provisional version of such a decision tree has been developed, based on the findings of Task 1, and is shown in Figures 2.1a to 2.1d. Potentially, a decision tree such as this could be used to assess the quantities of forest bioenergy supplied and consumed by a given project, that are likely to be associated with negative to low, moderate or high risks of significant GHG emissions. An illustration of such an application of the decision tree is given in Appendix 1. However, it should be stressed that the design of the decision tree in Figures 2.1a to 2.1d is provisional and is likely to require further refinement. Supporting notes to the decision tree are provided in Box 2.1.

In the context of the quantitative assessment of scenarios for bioenergy use undertaken in this project, the decision tree in Figures 2.1a to 2.1d was used to inform the design of two different sets of assumptions describing approaches to forest management and wood use. These two approaches were referred to in the modelling of the management of forest areas and patterns of wood use involved in the supply of forest bioenergy, as part of Task 3 of this project. The purpose of developing two different sets of assumptions about approaches to forest management and wood use was to permit an exploration of the sensitivity of results for scenarios for bioenergy consumption and supply with respect to these factors, which had already been determined as an important issue in Task 1. Further details are given in Section 4.8.3 of this report.

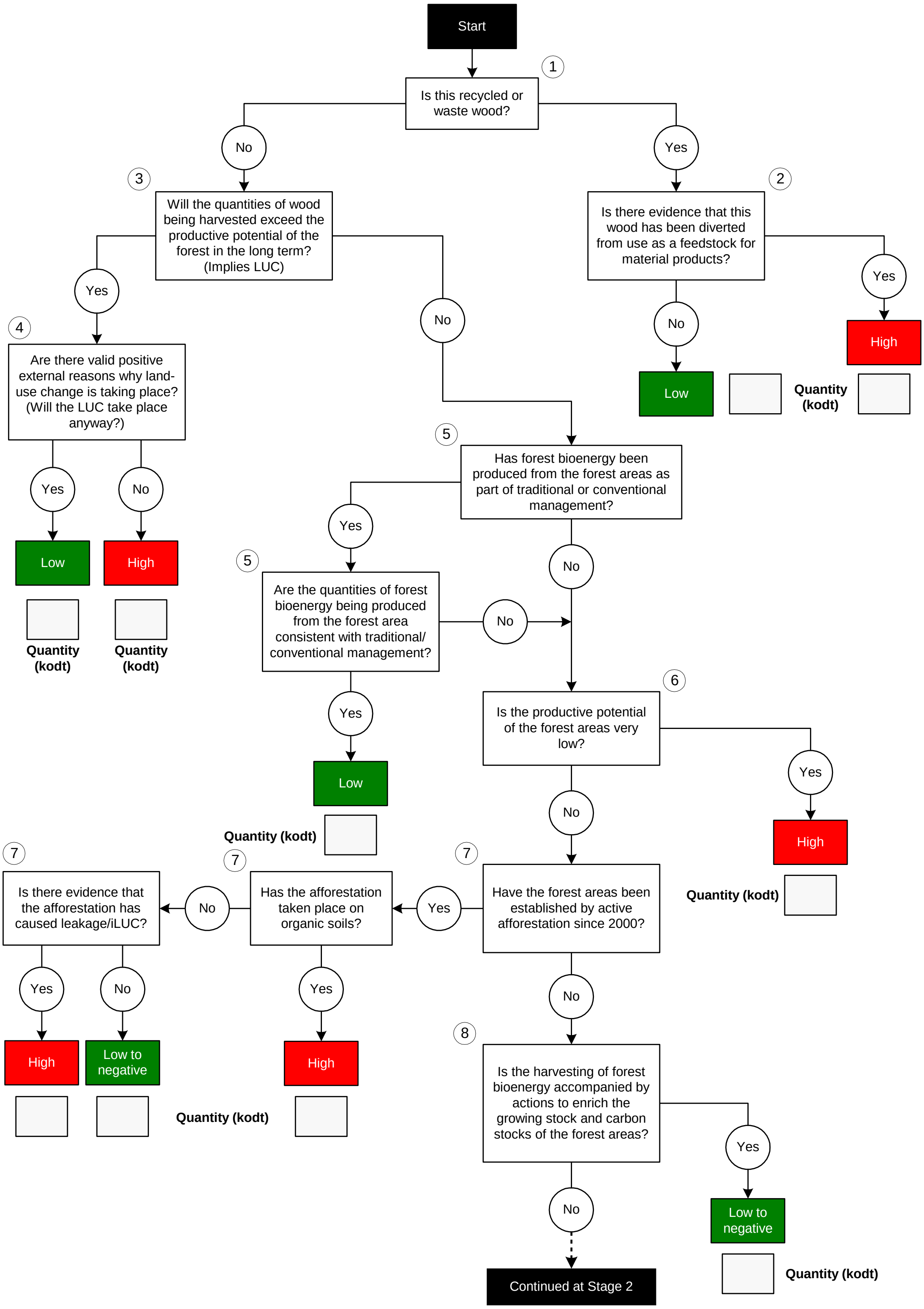

Figure 2.1a. Provisional decision tree for the systematic qualitative assessment of sources of forest bioenergy (part 1). Numbers in circles refer to supporting notes in Box 2.1.

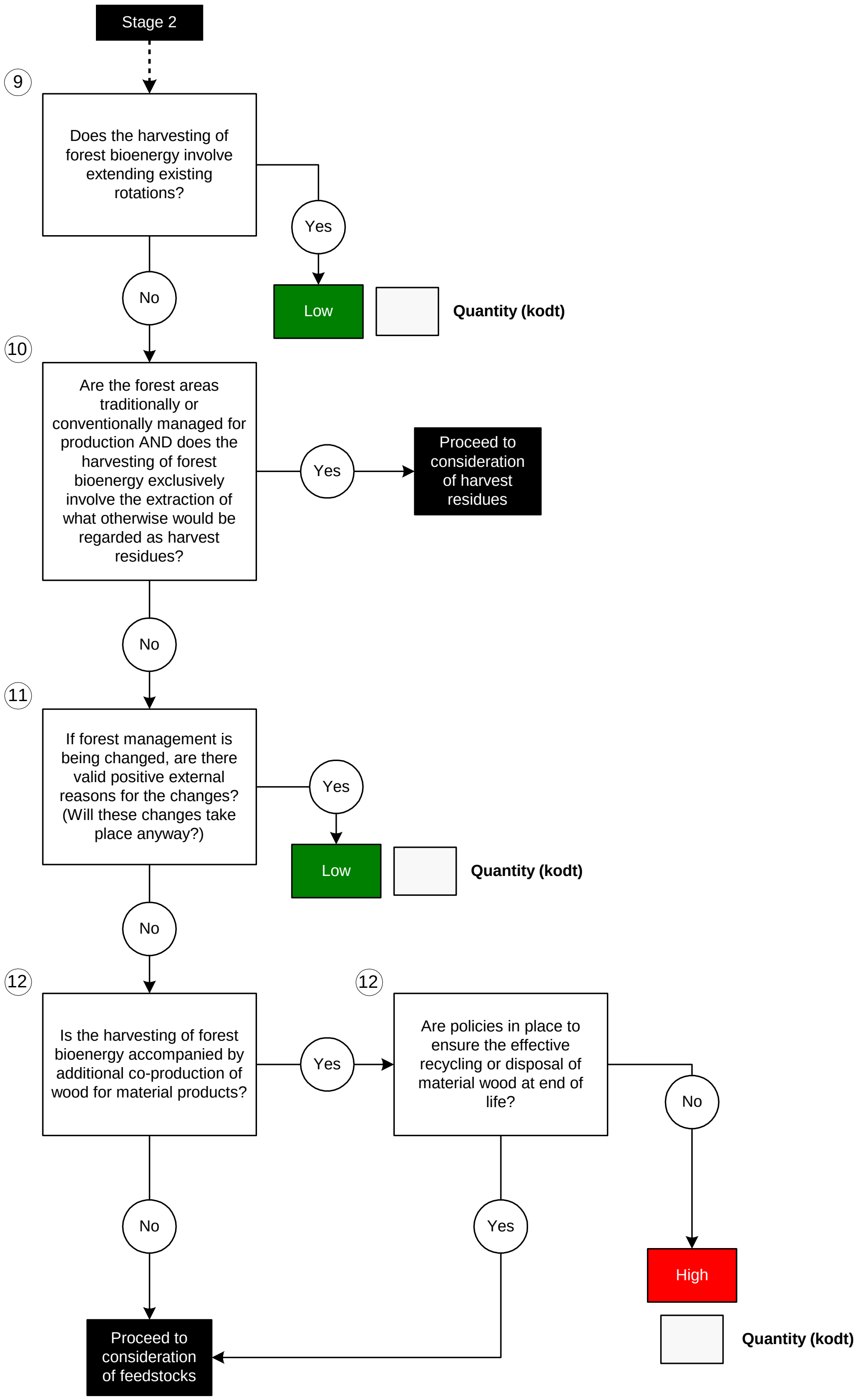

Figure 2.1b. Provisional decision tree for the systematic qualitative assessment of sources of forest bioenergy (part 2). Numbers in circles refer to supporting notes in Box 2.1.

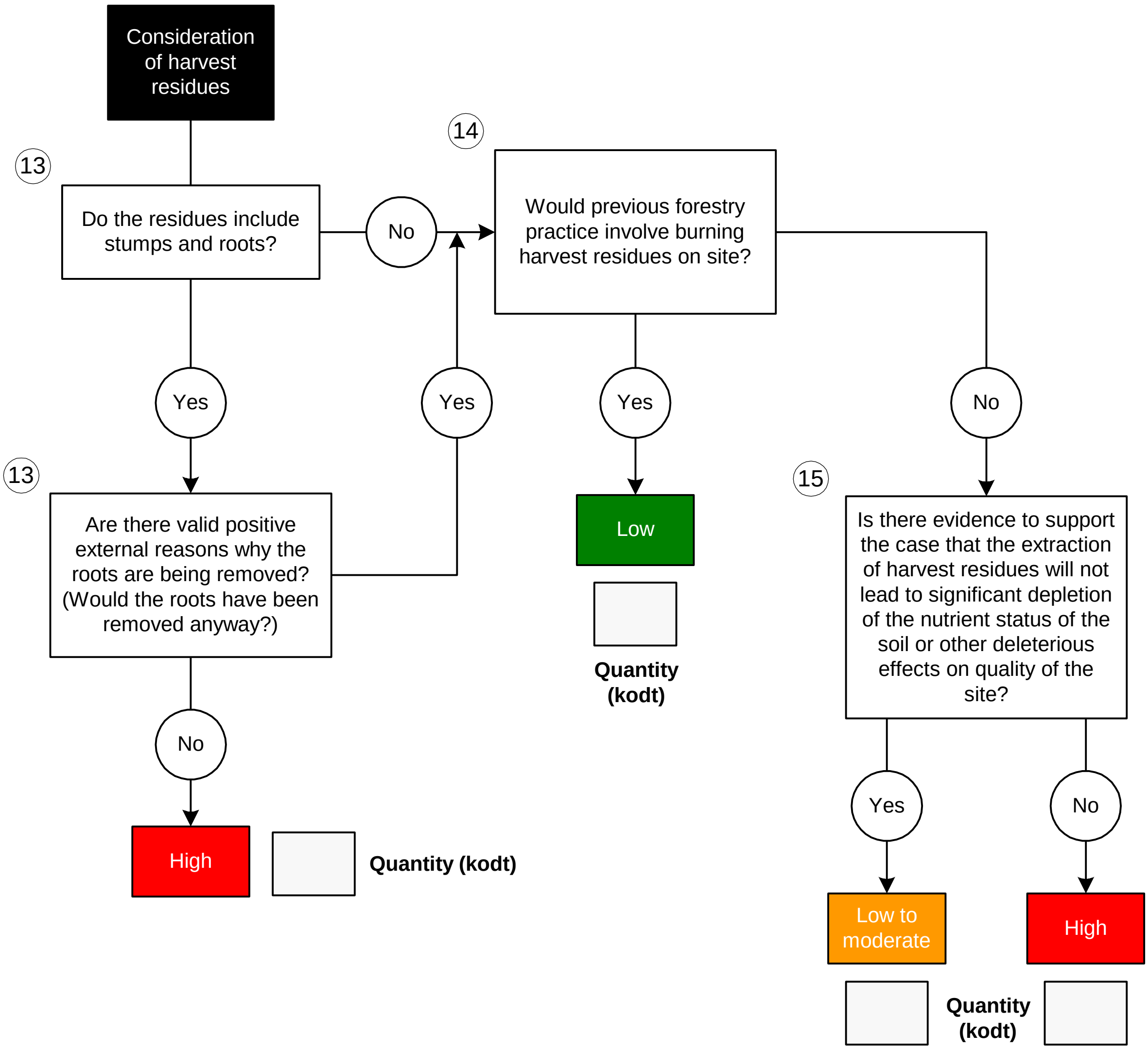

Figure 2.1c. Provisional decision tree for the systematic qualitative assessment of sources of forest bioenergy (part 3). Numbers in circles refer to supporting notes in Box 2.1.

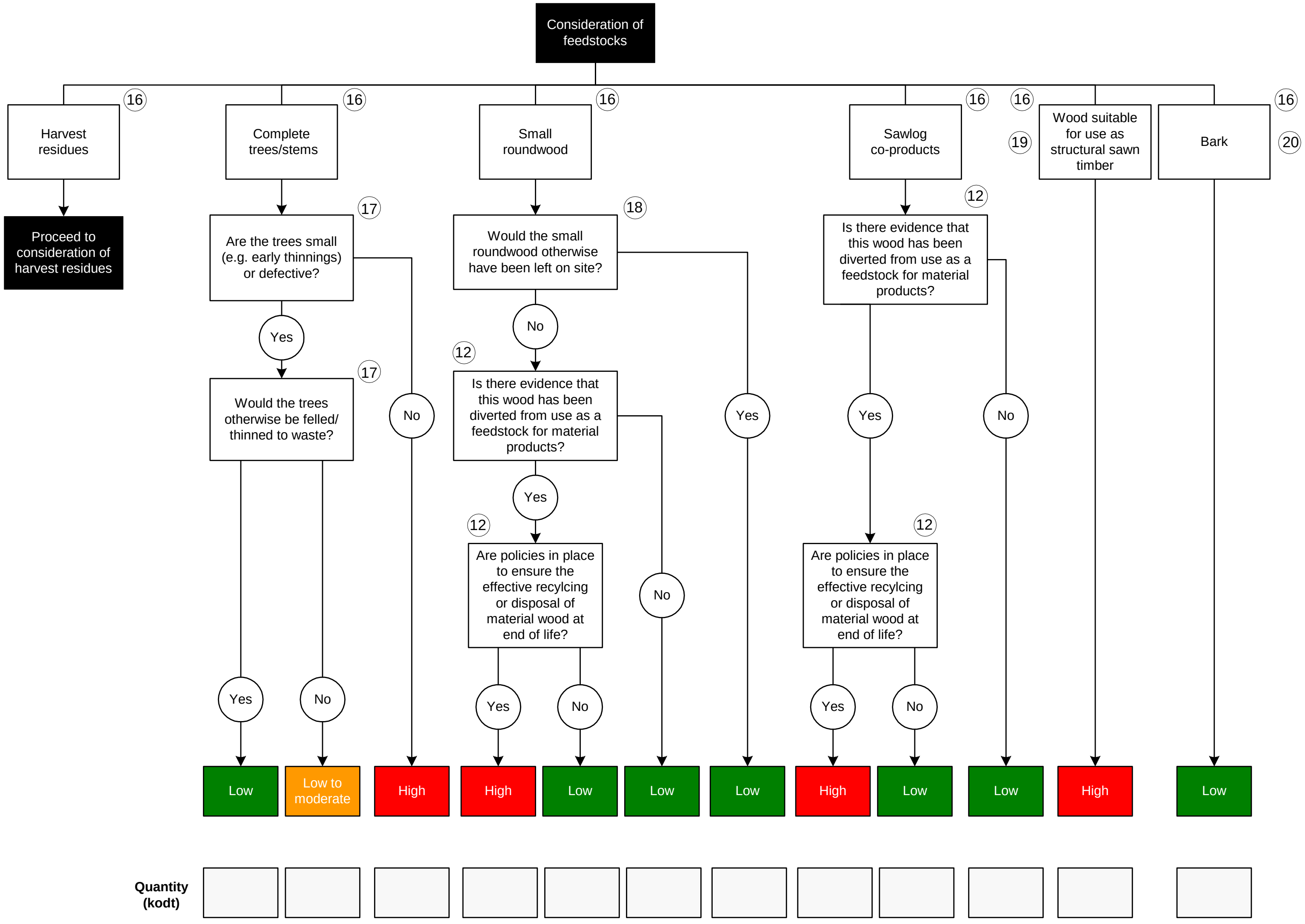

Figure 2.1d. Provisional decision tree for the systematic qualitative assessment of sources of forest bioenergy (part 4). Numbers in circles refer to supporting notes in Box 2.1.

Box 2.1 Notes in support of Figures 2.1a-d

General note: It is important to stress that the qualitative assessment as represented by the decision tree in Figures 2.1a-d is intended for application as part of a wider assessment of the sustainability of forest management and wood production. There are a number of existing examples of sustainability assessment methodologies addressing a range of environmental, ecological, economic and social criteria.

The following notes relate to the circled numbers in Figures 2.1a-d.

1. See Glossary for definitions of recycled wood and waste wood.
2. The determination of a methodology for making an assessment to address this question is beyond the scope of this current project. It may be difficult to specify a generic methodology because the approach to such an assessment may be very context-specific. Note that the approach here is precautionary, in that a presumption is made that, in terms of GHG emissions, the consumption of wood for forest bioenergy should not involve diversion from use for material wood products. This may not be valid in all possible circumstances (see for example Note 12 and some of the results presented in Matthews *et al.*, 2014b).
3. Essentially, this question aims to test for the occurrence of deforestation, or forest degradation from the perspective of long-term sustainable yield.
4. There may be specific, although possibly limited circumstances in which a valid decision is taken to remove or greatly reduce tree cover. For example, this may sometimes occur to achieve wider environmental or ecological objectives, such as the restoration of certain types of habitat, such as heathland. Deforestation may also be driven sometimes by unavoidable development activities, which take place regardless of whether any felled trees are utilised for bioenergy or for material wood products. This question aims to identify such situations. The definition of "valid positive external reasons" would need to be carefully stated and justified.
5. These two questions aim to test for situations in which the harvesting of wood and its use for bioenergy are consistent with business-as-usual practice (in terms of forest management and the quantities of bioenergy produced). The definition of "traditional or conventional management" would need to be carefully stated and justified. It is suggested that business-as-usual production of forest bioenergy should be regarded as non-controversial in terms of biogenic carbon emissions (see for example Sections 3.5, 3.6 and 4.10 in the Task 1 report).
6. Harvesting of wood, to produce forest bioenergy and/or material wood products, in areas of forest that are not already under management for production, and which have low long-term productive potential, is likely to involve significant risks of high biogenic carbon emissions (see for example Section 3.10 in the Task 1 report). This implies the possibility of identifying a lower threshold for relevant forest areas, expressed in terms of maximum long-term potential stemwood production, in units of $m^3\ ha^{-1}\ yr^{-1}$. This threshold may need to be determined at a national, sub-national or local scale. The identification and proposal of specific thresholds is beyond the scope of this current project.

Box 2.1 (continued) Notes in support of Figures 2.1a-d

7. These questions aim to test for situations in which bioenergy production is occurring from forest areas that have been recently afforested. If this afforestation is occurring/has occurred on sites where soils have high organic carbon content (e.g. peatlands), then this is very likely to involve high risks of associated GHG emissions. If the afforestation is leading to iLUC, then this is likely to involve high risks of overall GHG emissions, although the actual impacts may depend strongly on the specific situation and may require careful assessment. The determination of a methodology for making an assessment to address this question is beyond the scope of this current project. There are examples of existing methodologies for assessing or avoiding risks of iLUC (see for example LIIB, 2012). Provided that afforestation avoids iLUC and sites with soils with high organic carbon content, it is suggested that the production of forest bioenergy from such areas should be viewed as non-contentious from the perspective of biogenic carbon emissions, particularly in the case of new/future afforestation (see for example Sections 3.6 and 3.16 of the Task 1 report). The definitions of "afforestation" and "high organic carbon content" would require careful elaboration. The cut-off year of 2000 adopted in the decision tree is notional, and may require more detailed specification at national, sub-national or local scale. These specifics are beyond the scope of this project. The importance of the general note stated at the opening of this information box must also be re-stressed.
8. There may be specific, although possibly limited circumstances in which the increased extraction of harvested wood from forest areas is associated with active efforts to improve the forest growing stock. An example might involve interventions to restore forest areas that were previously degraded (through historical LU/LUC or as a result of long-term or catastrophic natural disturbance). It is suggested that such situations should be regarded as non-contentious in terms of biogenic carbon emissions (see for example Section 3.16 of the Task 1 report). This question aims to test for such situations. However, the definition of "actions to enrich the growing stock and carbon stocks" would need to be carefully stated and justified. The importance of the general note stated at the opening of this information box must also be re-stressed.
9. There may be specific, although possibly limited circumstances in which increased extraction of harvested wood from forest areas is associated with active efforts to extend the rotations applied to affected forest stands. An example might involve the conversion of forest areas, traditionally or conventionally managed as coppice on relatively short rotations, to high forest. It is suggested that such situations should be regarded as non-contentious in terms of biogenic carbon emissions. This question aims to test for such situations. However, the definition of "active efforts to extend the rotations applied to affected forest stands" would need to be carefully stated and justified. The importance of the general note stated at the opening of this information box must also be re-stressed.
10. This question aims to test for situations in which, essentially, the existing management of forest areas is not being changed from traditional or conventional practice, with the exception that there is increased extraction of harvest residues for bioenergy. See Glossary for definition of harvest residues. The definition of "traditionally or conventionally managed for production" would need to be carefully stated and justified.

Box 2.1 (continued) Notes in support of Figures 2.1a-d

11. There may be specific, although possibly limited circumstances in which a valid external decision is taken to change the management of forest areas, which involves increased harvesting of wood but within the constraints of the long-term potential for sustainable yield. The presumption in this context is that the decision is taken on wider environmental or ecological grounds. An example might involve the introduction or restoration of active management in overstocked forest stands as part of the restoration or creation of specific types of habitat. This question aims to identify such situations. The definition of "valid positive external reasons why the management of forest areas is being changed" would need to be carefully stated and justified.
12. Generally, presumptions have been made that, in terms of impacts on GHG emissions: (a) the co-production of forest bioenergy alongside material wood products is to be preferred; (b) the diversion of harvested wood from use for material wood products, for use as bioenergy instead, should be avoided. However, it should be noted that there are likely to be important exceptions. One particularly important issue concerns the approaches taken to the recycling or disposal of material wood products at end of life, which can have widely varying impacts on GHG emissions (see for example Matthews *et al.*, 2014b). If effective policies for recycling and/or disposal are not in place, then the presumptions in favour of material wood products are harder to justify. These questions aim to test for relevant situations. The definition of "policies … to ensure the effective recycling or disposal of wood at end of life" (or the lack of such policies) would need to be carefully stated and justified.
13. A presumption is made that the extraction of tree stumps and roots should be avoided, due to the disruption this would cause to the site and soil, and consequent impacts on soil carbon stocks. However, there may be specific, although possibly limited situations in which tree roots are removed, perhaps as part of conventional practice. An example might involve actions to control an endemic tree disease affecting certain sites. These questions aim to identify relevant situations. However, the definition of "valid positive external reasons why roots are being removed" would need to be carefully stated and justified. The importance of the general note stated at the opening of this information box must also be re-stressed.
14. In some forest areas, it has been conventional practice to burn harvest residues on site, as part of preparation for restocking through tree regeneration or replanting. If this practice is changed so that harvest residues are extracted instead of burnt, this should have negligible impacts on biogenic carbon emissions. This question aims to test for such cases.
15. Forest sites can be vulnerable to the excessive removal of harvest residues, particularly if this includes tree foliage. The nutrient status of the soil can be affected, as can soil acidity. The physical structure of the soil may be damaged if harvest residues (e.g. mats of branchwood) are not present to protect it from heavy machinery. This question aims to test for such situations. The determination of a methodology for making an assessment to address this question is beyond the scope of this current project. The importance of the general note stated at the opening of this information box must also be re-stressed.
16. See Glossary for definitions of various types of wood feedstock.

Box 2.1 (continued) Notes in support of Figures 2.1a-d

17. These questions aim to identify situations in which forest bioenergy is being produced from relatively small trees harvested as early thinnings in young stands, or from defective trees (see Section 2.3 of the Task 1 report). Early thinnings and the removal of defective trees can be important for the improvement of forest stands later in their rotations. This may be from an environmental perspective (e.g. avoiding overstocking and the suppression of understorey vegetation or potential loss of habitats), and/or from the point of view of wood production (e.g. favouring the subsequent growth of better quality trees for material wood production). In some situations, early thinnings as part of the improvement of forest stands may involve felling and discarding of trees on site in the forest. This question aims to restrict the harvesting of complete trees or stems for use as bioenergy to situations involving early thinnings and/or defective trees. Clearly evidence would be needed to verify the existence of such situations. The definitions of "small trees", "early thinnings", "defective trees" and "stemwood" (in this last case see Glossary) would need to be carefully stated and justified. These definitions may need to be specified on a national, sub-national or local scale. The determination of such definitions is beyond the scope of this current project. The importance of the general note stated at the opening of this information box must also be re-stressed.
18. There may be specific, although possibly limited circumstances in which trees are harvested from forest stands primarily for the production of sawlogs, whilst local uses do not exist for any associated small roundwood, which is consequently discarded and left on site in the forest. In such situations, it is suggested that the extraction of the small roundwood for use as bioenergy should be viewed as non-contentious in terms of biogenic carbon emissions. This question aims to identify where these situations are occurring. Clearly evidence would be needed to verify the existence of such situations. The determination of a methodology for making such an assessment is beyond the scope of this current project. The importance of the general note stated at the opening of this information box must also be re-stressed.
19. Generally, a presumption is made that harvested wood suitable for use as structural sawn timber should not be used for bioenergy. However, it should be noted that this is a precautionary measure, which may not be valid in all possible circumstances (see for example Note 12 and some of the results presented in Matthews *et al.*, 2014b).
20. Generally, a presumption is made that the use of bark for bioenergy is non-contentious in terms of GHG emissions, even in situations where bark is being diverted from non-bioenergy uses (see for example Matthews *et al.*, 2014b).

3. Scenarios for biomass use in the EU

3.1. Purpose

The purpose of this section is to describe work undertaken as part of Task 2 of this project. Task 2 involved the development of scenarios for biomass use in the EU that take into account types of biomass sources (inside and outside the EU) and relevant bioenergy technologies that are available now and are likely to be used in the future. This task builds further on previous work already undertaken on the development of scenarios for biomass use for energy within the EU.

The aim of Task 2 is to develop scenarios for biomass use for electricity and heat generation in the EU in 2020, 2030 and 2050. Within this task one *reference* scenario consistent with existing policies in the EU and without additional GHG and renewable energy targets after 2020 was developed, along with five *decarbonisation* scenarios assuming different levels and sources of domestic and imported biomass use for electricity and heat generation in the EU for 2030 and 2050. Biomass use was quantified at Member State level for different biomass sources and for both domestic and imported feedstock.

3.2. Approach

A stepwise approach was used for the development of the scenarios, which is shown in Figure 3.1 and described in further detail below:

Step 1 – A review of existing biomass and scenario studies was carried out, with the aim of identifying the relevant studies that can be used for the development of the scenarios for biomass use for this study, as well as to identify studies that quantified biomass potentials and costs (see Appendix 2).

Step 2 – Based on the review, a set of scenario storylines was defined. These storylines described the main assumptions for a range of relevant parameters, e.g. the GHG emissions reduction target, the target for renewable energy sources, the contribution from bioenergy consumption, the sources and types of domestic biomass, and the application of sustainability criteria (see Section 3.3.3).

Step 3 – Biomass potentials and costs were determined for each of the scenarios, based on available data from the reviewed studies, and additional assumptions that were in line with the storyline descriptions developed for the scenarios.

Step 4 – The VTT-TIAM model was used to simulate the final consumption of biomass for energy and the technologies used, based on the demand, the biomass costs and potentials, and other scenario settings.

Step 5 – The results of the modelling using VTT-TIAM were analysed, summarised and described. In addition, the final biomass production results were downscaled to member state level for further analysis of the biogenic carbon emissions in Task 3.

The review of existing biomass and scenario studies undertaken in Step 1 identified a number of studies that have informed the development of scenarios in this project. An overview of the main studies of relevance is provided in Appendix 2. Two studies should be highlighted as having provided much of the supporting data, and having formed the basis for much of the development of the scenarios. These two studies are the EFSOS II project of the forestry and wood products sector (UNECE and FAO, 2011), and the Biomass Futures project, of greater relevance to the agricultural sector (Elbersen *et al.*, 2012, 2013). Summary descriptions of these studies are provided, respectively, in Appendices 3 and 4.

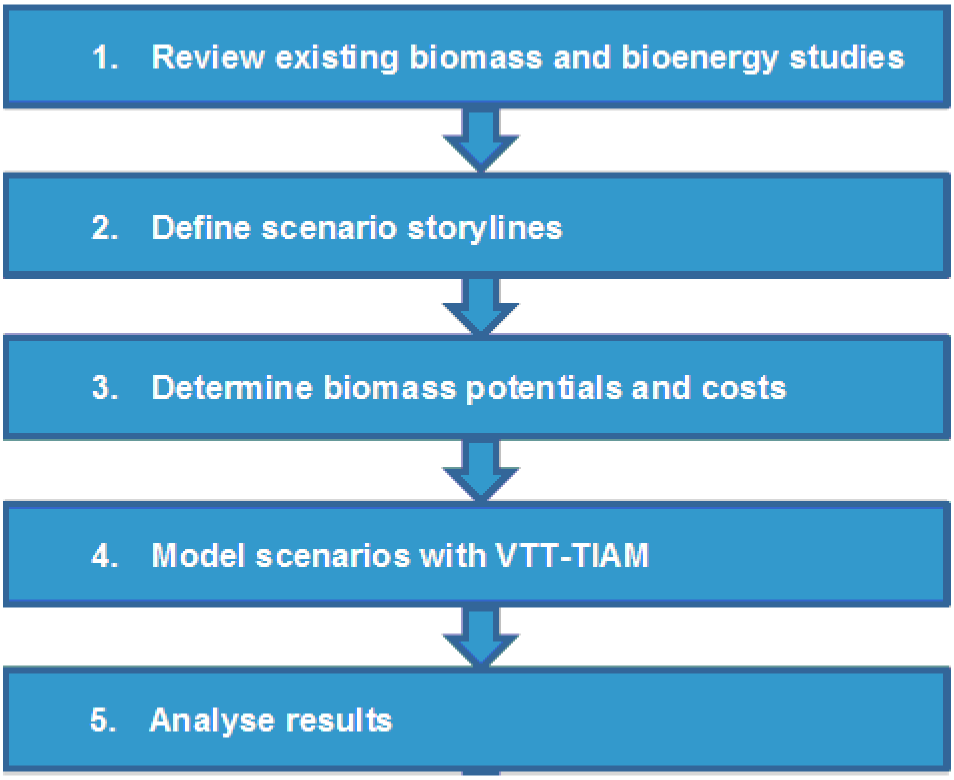

Figure 3.1. Steps in the development of scenarios for biomass use in Task 2.

3.3. Overview of scenarios

For this study, six scenarios of biomass use for energy were developed, building on the PRIMES scenarios 2013 produced for the European Commission in 2013 (see Appendix 2). These PRIMES scenarios were used for the impact assessment of the communication on the policy framework for climate and energy in the period from 2020 up to 2030. The PRIMES reference scenario was used, and five variants of the EEMRES30 decarbonisation scenario were developed. The EEMRES30 scenario involves a 40% reduction target for GHG and a 30% target for renewable energy.

The following six scenarios were thus developed in this study:

- **A – 'Reference':** Following the PRIMES 2013 reference scenario without additional GHG and targets for renewable energy sources after 2020.
- **B – 'Carry on/unconstrained use'**: Decarbonisation scenario with a 40% GHG reduction target and 30% target for renewable energy sources for 2030, but without sustainability criteria for solid and gaseous biomass (see Section 3.3.3). This scenario has the highest use of biomass for energy, coming from imports and domestic production and from forest and agricultural biomass sources.
- **C1 – 'Carry on/imported wood':** Decarbonisation scenario with a 40% GHG reduction target and 30% target for renewable energy sources for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the additional biomass comes from imported forest-based biomass, hence the shorthand title for this scenario. However, it should be noted that the scenario also involves some increases in the importation of biofuels.
- **C2 – 'Carry on/domestic crops':** Decarbonisation scenario with a 40% GHG reduction target and 30% target for renewable energy sources for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the additional biomass comes from domestic agriculture-based biomass.
- **C3 – 'Carry on/domestic wood':** Decarbonisation scenario with a 40% GHG reduction target and 30% target for renewable energy sources for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the additional biomass comes from domestic forest production.
- **D – 'Back off'**: Decarbonisation scenario with a 40% GHG reduction target and 30% target for renewable energy sources for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Bioenergy consumption is lower, compared to the reference scenario, and replaced by other renewable energy sources.

3.3.1. Key principles and approaches in developing scenarios

It is important to understand the principles and approaches that have been applied in this project for the development of the details of the scenarios describing possible future consumption of biomass for energy in the EU. These principles and approaches have been referred to not only in the work of Task 2, but also in the modelling for the assessment of biogenic carbon and non-biogenic GHG emissions, as undertaken in Tasks 3 and 4. Specifically, in considering the details of the development and assessment of the scenarios, it is worth recalling some of the essential principles of consequential LCA, and it is important to understand how the approach taken relates to these principles.

The principles of consequential LCA, and their relevance to this project, have been discussed extensively in Section 4 of the Task 1 report for this project (Matthews *et al.*, 2014a), in particular in Section 4.3. The essential purpose of consequential LCA may be stated as to assess the impacts that are likely to occur as a result of taking a specified policy or commercial decision. For the purposes of this project, the impacts of interest are those that affect GHG emissions, including those due to biogenic carbon. In order to assess these impacts, it is necessary to model 'how the world will change' if the decision is taken, as opposed to the counterfactual scenario of how the world would develop if the decision is not taken. In some contexts, this may imply undertaking an economic analysis of a decision taken in isolation (e.g. the setting of a simple target for bioenergy consumption), with no consideration of any other possible constraints or interventions (see for example JRC, 2010, pages 71 and 72). However, in reality, economic systems do not operate in the absence of constraints, and it is important to allow for this in the development and assessment of any meaningful scenarios. Furthermore, in modelling how the world will change under a given scenario, it is necessary to consider how the decision being assessed may be implemented through, generally, a combination of new activities and changes in existing activities. Typically, there will be different possible approaches to taking such a set of implementing actions, which may have different outcomes in terms of impacts (on GHG emissions). It follows that, in order to achieve the objectives of this project, it is necessary to develop reasonable storylines describing the combinations of actions likely to be involved in implementing policy decisions towards consumption of bioenergy in the EU, allowing for any relevant constraints.

As strongly stressed in the discussion in Section 4 of the Task 1 report for this project, the specific approach to consequential LCA adopted for a particular assessment depends on the research question to be addressed. Accordingly, the approach to the development and assessment of scenarios in this project is derived from the research question set in this project, as stated in Section 1.2.2.

Fundamentally, the five scenarios defined for the purposes of this project represent options for decisions that may be taken to enhance or reduce future contributions made by biomass sources to the supply of energy in the EU. In addition, the scenarios permit an assessment of the sensitivity of impacts to the approaches taken to the use of biomass, for example, by placing greater or lesser emphasis on:

- Domestic or imported biomass supply
- Agricultural or forest biomass sources
- Biomass production relatively constrained or unconstrained by consideration of wider environmental impacts (see Section 3.3.3).

Hence, part of the development of the scenarios has involved specifying the relative prioritisation given to total bioenergy consumption, and also to the types of biomass sources involved in bioenergy supply.

As part of Task 3 (see discussion in Sections 4.6 to 4.8), further investigation is made of the dependence of outcomes, in terms of biogenic carbon emissions, on the approaches taken to producing the levels of biomass specified by the scenarios developed in Task 2.

This is particularly important in the case of forest bioenergy, for which biogenic carbon emissions can vary considerably, depending on the approaches taken to forest management and wood use (see the Task 1 report for this project, Matthews *et al.*, 2014a).

3.3.2. Brief description of scenario storylines

In the storyline for the reference scenario (the basis for the development of Reference Scenario A), only limited measures are taken that lead to higher CO_2 prices, whilst in the decarbonisation scenarios, higher renewable energy production is encouraged through the carbon credit market. According to the PRIMES EEMRES30 decarbonisation scenario, the ETS CO_2 price increases from €10 per tonne CO_2 in 2020, to €10.8 in 2030 and to €152 in 2050. In the reference scenario, the CO_2 price increases more quickly (€35 in 2030), but is lower in 2050 (€100). These higher prices go together with specific stimulation of bioenergy demand and production, giving bioenergy an advantage over other renewable energy sources.

In most of the decarbonisation scenarios (Scenarios C1, C2, C3 and D), strict GHG mitigation criteria and measures are assumed, i.e. decarbonisation of the economy is taken very seriously. Bioenergy production is strongly encouraged, provided that it delivers significantly lower GHG emissions than fossil alternatives. In these scenarios, a GHG saving target of at least 60% applies to all solid and gaseous biomass pathways, in addition to the biofuel pathways. A very important difference compared to the reference scenario, is that this GHG emissions mitigation requirement should also include compensation for emissions from indirect land use changes caused by biomass cropping in the EU, which encourages iLUC-free or low-iLUC biofuel use (e.g. agricultural residues). In Scenarios C1 and C3, this encourages the use of forest biomass, from imported sources (particularly Scenario C1) and domestic sources (particularly Scenario C3). In Scenario C2, the use of forest biomass is more strongly restricted. For example, this may be achieved through the application of very restrictive criteria for determining sustainable forest management, which would decrease the potential for forest-based biomass production. In Scenario C2, the most resource-efficient biomass sources (e.g. waste and forest/agricultural residues) become more scarce and expensive, which leads to dedicated perennial biomass sources becoming more attractive, particularly when these can be produced on marginal and abandoned land to prevent iLUC.

In the storyline for Scenario D (‘Back off’), the use of bioenergy is de-prioritised as part of moves towards decarbonisation. Levels of biomass use for energy are lower in this scenario, even compared with the reference scenario. However the use of bioenergy is subject to the same stronger constraints as in Scenarios C1, C2 and C3, compared to the existing constraints applied in the Reference Scenario A. In the case of the other high-bioenergy decarbonisation scenario B (‘Carry on/unconstrained use’), bioenergy production is strongly encouraged as in Scenarios C1, C2 and C3. However, the stronger constraints on bioenergy use, as applied in Scenarios C1, C2 and C3, are not applied in the storyline for Scenario B. Biomass is the highest under Scenario B, produced from a range of sources, i.e. agriculture and forestry and, in the case of forest biomass, both domestic and imported sources.

For the purposes of this project, for all scenarios, it was assumed that all biomass of agricultural origin consumed for heat and/or power generation in the EU region would also be produced in the EU region.

3.3.3. Relevance of sustainability criteria

It is important to understand how 'sustainability criteria' have been referred to in developing the scenarios for biomass use in Task 2. This was appropriate because some sustainability criteria are already applied to some bioenergy sources (more generally in forestry), and this influences the potential for biomass supply. A key instrument in this respect is the Renewable Energy Directive.

The main sustainability criteria defined in the Renewable Energy Directive include:

1 A minimum requirement for GHG emissions savings (see Article 17(2)), specifically a target for GHG savings of 60% is assumed to apply for all biofuel installations post 2020.
2 Bioliquids shall not be produced from material from specified sources, i.e. (a) land with high biodiversity value; (b) land with high carbon stocks, unless the status of the land is not changed; (c) drained peatland that was previously undrained.
3 Agricultural materials produced in the EU must be produced in accordance with existing regulations on good agricultural practices.

These criteria, and the accounting for iLUC in the GHG savings based on Laborde (2011), were referred to in determining the biomass potentials and in constraining the selection of bioenergy crops in some scenarios. In the development of the individual scenarios, the application of sustainability criteria was reflected by selecting appropriate underlying scenarios from the EFSOS II and Biomass Futures studies in determining biomass potentials (see Section 3.5).

The sustainability criteria applied in the Reference Scenario A followed the Renewable Energy Directive and only applied to biofuels and bioliquids. For the decarbonisation scenarios (Scenarios C1, C2, C3 and D), these criteria were assumed to be extended to solid and gaseous bioenergy sources, in determining biomass potentials.

In Scenarios C1, C2, C3 and D, the storylines also assume additional policy measures are taken to limit the use of scarce resources, such as water, and prevent the loss of biodiversity and related ecosystem services. This is achieved by limiting the removal of biomass from high biodiversity areas or lands with a high carbon stock (e.g. peatlands), see Section 3.5 and Appendices 3 and 4 for further details. Constraints are also applied on the use of irrigation water in energy cropping, as this is also seen as an increasingly scarce resource particularly in arid regions. This implies that the potential for dedicated energy cropping in arid regions that have large areas of marginal/abandoned land is limited, as it becomes more complicated to produce enough biomass per hectare to reach the high GHG saving target of 60% relative to fossil fuel alternatives. As explained in Section 3.3.2 the extended and additional application of sustainability criteria was assumed not to occur in the storyline for Scenario B.

It is also important to highlight that the preceding discussion describes how sustainability criteria were referred to in developing distinct storylines for the various scenarios in Task 2. However, the assessment of biogenic carbon emissions in Task 3 (see Section 4) further elaborated this analysis to explore sensitivities to approaches to biomass production, particularly in the case of forest management and wood utilisation.

Encouraging high bioenergy use, at the same time as applying stricter sustainability constraints, requires the encouragement of technologies that also lead to increased biomass demand and efficient use in the energy system. The time to market of highly efficient bioenergy technologies needs to be reduced. This can only happen if enough research and development resources are invested. Hence as part of the storylines for the high-bioenergy Scenarios B, C1, C2, C3, it is assumed that:

- Biomass use in the electricity and heat pathways (including for transport) is encouraged, particularly when based on local residual biomass resources. This is done by making decentralised and small-scale conversion technologies more attractive (economically, but also by, for example, faster development of the grid and stimulation of direct local heat use). However, this requires clean technologies to prevent air pollution, in order to comply, for example, with the recently proposed clean air quality package.
- Conventional biofuel production, based on food crops, is no longer supported in the EU after 2020, and is exchanged for waste and residue-based biofuels, and advanced biofuel production pathways, in combination with biorefineries and greater electricity and hydrogen use in transport. This could be stimulated through accelerating electric car technology development and increasing the share of electricity-based public transport, as well as larger investments in research and development into advanced fuel technologies.
- Biogas technologies are made more efficient by stimulation measures, including obligations to use waste heat, and further deployment of local residual biomass resources.

A detailed specification of the assumptions involved in the scenario storylines is provided in Table 3.1. Further details on how these assumptions are parameterised in the VTT-TIAM model are discussed in Section 3.4.

Table 3.1 Summary of scenario storyline assumptions

Scenarios	GHG emission reduction target for 2030[1]	Renewable Energy target for 2030[2]	Contribution from bioenergy consumption after 2020	Domestic biomass types	Biomass imports[3]	Sustainability criteria[4]
A – 'Reference'	-20% by 2020 and continuation of ETS reductions (in total about 30% in 2030)	None	Increasing slightly after 2020	Forest biomass (emphasis on existing, traditional consumption of wood for energy, forest residues and waste wood, lower emphasis on stemwood) and agricultural biomass (mainly annual crops and residues)	Low imports of forest biomass and biofuels	Existing criteria in the RED continue to apply to biofuels in transport/bioliquids, in electricity/heating, but not to other biomass used in electricity/heating, food based biofuels no longer receive support after 2020
B – 'Carry on/ unconstrained use' (no sustainability criteria for solid and gaseous biomass)	-40%	30%	High bioenergy consumption	Very high forest and agricultural biomass use compared to Scenario A. May involve significant consumption of stemwood in addition to harvesting residues and waste wood	High imports of forest biomass and biofuels	Existing criteria in the RED continue to apply to biofuels in transport/bioliquids, in electricity/heating, but not to other biomass used in electricity/heating, food based biofuels no longer receive support after 2020

Table 3.1 (continued) Summary of scenario storyline assumptions

Scenarios	GHG emission reduction target for 2030[1]	Renewable Energy target for 2030[2]	Contribution from bioenergy consumption after 2020	Domestic biomass types	Biomass imports[3]	Sustainability criteria[4]
C1 – 'Carry on/ imported wood' (sustainability criteria for all bioenergy and emphasis on imports)	-40%	30%	High bioenergy consumption	Slightly higher compared to Scenario A, but main increase comes from imports of forest biomass	High imports of forest biomass and biofuels. Sub-scenarios for source region forest biomass will be assessed in Task 3	Existing criteria in the RED continue to apply to biofuels in transports/bioliquids, in electricity/heating and are extended to solid and gaseous biomass, food based biofuels no longer receive support after 2020. Additionally, iLUC is accounted for (according to Laborde, 2011) when determining GHG emissions savings, which affects the selection of bioenergy types.
C2 – 'Carry on/ domestic crops' (sustainability criteria for all bioenergy and emphasis on domestic agricultural biomass)	-40%	30%	High bioenergy consumption	High use of agricultural biomass including large scale cultivation of perennial crops in addition to biomass use assumed in Scenario A	Low imports of forest biomass and biofuels	Same as Scenario C1

Table 3.1 (continued) Summary of scenario storyline assumptions

Scenarios	GHG emission reduction target for 2030[1]	Renewable Energy target for 2030[2]	Contribution from bioenergy consumption after 2020	Domestic biomass types	Biomass imports[3]	Sustainability criteria[4]
C3 – 'Carry on/ domestic wood' (sustainability criteria for all bioenergy and emphasis on domestic forest biomass)	-40%	30%	High bioenergy consumption	High use of forest biomass, compared with scenario A. May involve significant consumption of stemwood in addition to harvesting residues and waste wood.	Low imports of forest biomass and biofuels	Same as Scenario C1
D – 'Back off' (sustainability criteria for all bioenergy, but emphasis on other renewable energy sources)	-40%	30%	Lower bioenergy consumption compared to Scenario A	Forest biomass (existing, traditional consumption of wood for energy, and waste wood) and agricultural biomass (mainly residues)	Low imports of forest biomass and biofuels	Same as Scenario C1

Notes to Table 3.1:

1 This is the GHG emissions reduction target, relative to 1990 levels, assumed in the PRIMES scenario referred to in constructing each scenario. The GHG emissions reduction target has a strong influence on the selection of renewable energy technologies (including bioenergy) in the VTT-TIAM model. In constructing each scenario, it is assumed that contributions to GHG emissions from bioenergy due to biogenic carbon are zero. However, it is important to recognise that, in practice, the GHG emissions reductions target will not be met if contributions to GHG emissions from bioenergy due to biogenic carbon are significantly greater than zero (see Section 3.4.1). This is a fundamental research question being addressed by this project in Task 3.

2 This is the target for the share of energy consumption met by renewable energy sources assumed in the PRIMES scenario referred to in constructing the scenario for bioenergy consumption. Amongst other things, this informs decisions about the share of energy consumption met through consumption of bioenergy.

3 Details of the exporting countries are dependent on assumptions made in a sensitivity analysis of forest management and wood utilisation, which are defined in Task 3 of this project (see Section 4).

4 See Section 3.3.3.

3.4. The VTT-TIAM model

The VTT-TIAM model is a partial equilibrium model of the global energy system based on linear optimisation. Assuming efficient markets and perfect foresight, the model calculates a market equilibrium solution through cost minimisation for energy production, conversion and end use under specified energy demand projections, technology assumptions and policies (e.g. targets for emissions levels or global temperature). VTT-TIAM is a version of the original ETSAP-TIAM model (Energy Technology Systems Analysis Programme, The Integrated MARKAL EFOM System Integrated Assessment Model). The description of the ETSAP-TIAM model has been published by Loulou and Labriet (2008). The VTT-TIAM model applies the TIMES methodology and includes a number of modifications made at VTT. More details can be found in Appendix 5.

VTT-TIAM is a 'bottom-up', partial equilibrium model of the energy system including a large database of energy technologies. The representation of production chains starts from the extraction of energy resources and continues through a number of conversion and distribution steps, ultimately leading to end use, to provide a wide variety of energy services in five sectors (industry, residential, transportation, commercial and agriculture). A simplified outline of the structure of the VTT-TIAM model is shown in Figure 3.2.

VTT-TIAM also includes all GHG emissions and sources covered by the Kyoto protocol, and a simplified climate module that can be used to calculate atmospheric GHG concentrations, radiative forcing and changes in global mean temperature. However, it should be noted that not all of this functionality is entirely relevant to this current project, although some of it has been used to support and cross-check more detailed calculations.

VTT-TIAM represents the global energy system as 18 regions (e.g. in Europe these include Finland, Sweden, Norway, Denmark, the rest of Western Europe, and Eastern Europe). The model runs primarily in 5 or 10 year time steps up to the year 2100, while having a limited degree of intra-year variability in production and consumption of selected technologies and energy sources (e.g. day-night variation with solar power).

The main inputs to VTT-TIAM are:

- Energy resources – quantities, marginal costs of extraction
- Energy and emissions reduction technologies – investment costs, lifetimes, running costs, efficiencies, availability factors, emissions factors etc.
- Future energy demands, per energy service and time step
- Energy and environmental/climate policy – taxes, emission targets, etc.

It is also possible to set certain constraints, e.g. GHG emissions reduction targets, prices for emissions allowances and limitations on certain types of technologies, where these are relevant to the definition of scenarios. The total bioenergy demand is set as an input together with certain scenario-specific constraints, and the model is used to assess the most cost-effective biomass feedstocks, conversion technologies and sources of biomass in terms of regional origin.

The main model outputs are:

- Flows of energy and emissions, per energy source/emissions type, region and time step
- Investment, capacity and activity of energy and emissions reduction technologies
- Climatic variables, i.e. atmospheric GHG concentration, radiative forcing, temperature increase
- Marginal values of different energy sources/emissions types (as shadow prices from the optimisation).

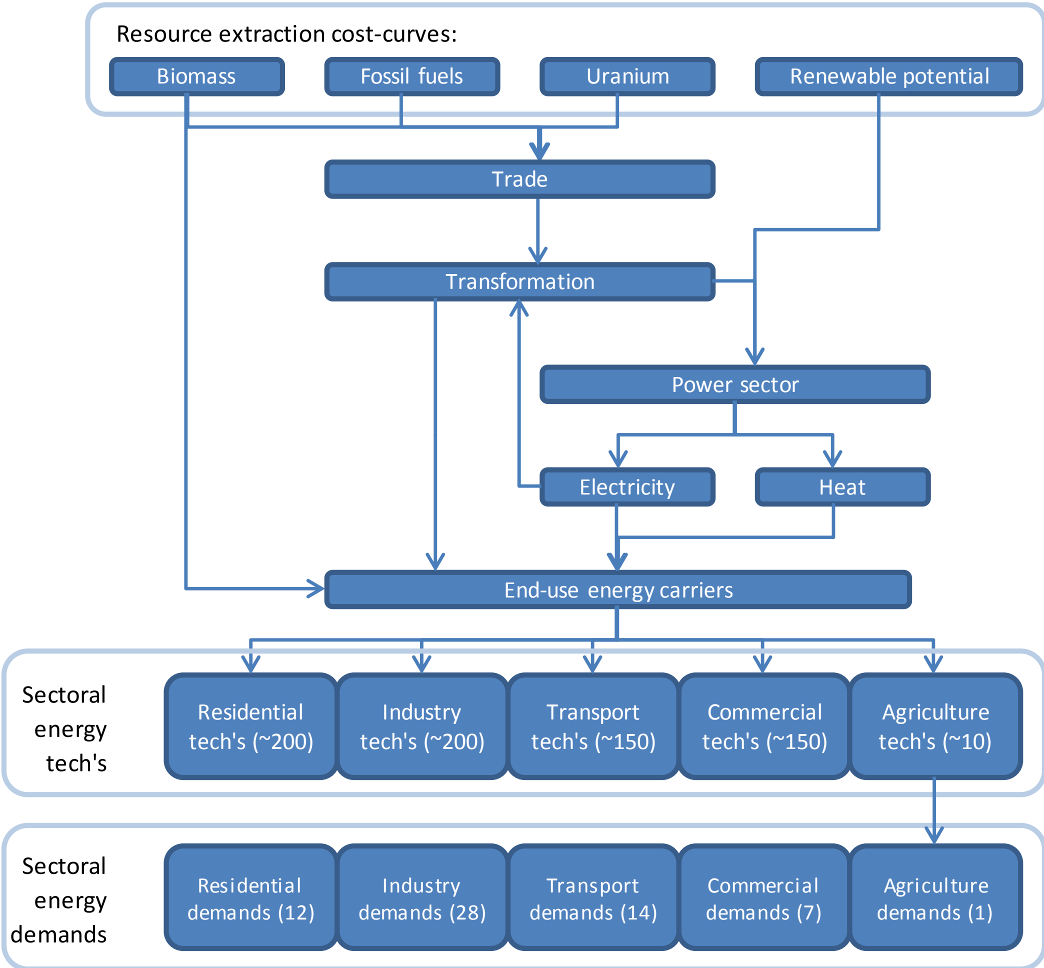

Figure 3.2. A simplified representation of the structure of the energy system in the VTT-TIAM model in one geographic region. The numbers in parentheses refer to the numbers of end-use energy technologies and the numbers of energy services delivered to sectors.

The VTT-TIAM model distinguishes several biomass sources including crops (7 production steps), agricultural biomass (2 production steps), wood (4 production steps), forest residues (3 production steps), waste (bio-waste, industrial waste wood, other industrial waste etc.), black liquor and biogas. For Task 3, it was necessary to further disaggregate these biomass sources into more specific crops and forest biomass types. It was also necessary to down-scale the scenario results to Member State level, because VTT-TIAM only distinguishes Western and Eastern Europe and the Scandinavian countries. Down-scaling was achieved through the analysis of relevant biomass potential studies and also through reference to relevant results produced by Task 3 (e.g. projections of biomass supply from forests made using the CARBINE model). The deployment of different bioenergy conversion technologies was also be identified, as the choice of technologies strongly determines the full life cycle carbon impact of the different biomass chains. Key bioenergy conversion technologies considered include direct combustion, gasification, pyrolysis, BioSNG production and anaerobic digestion.

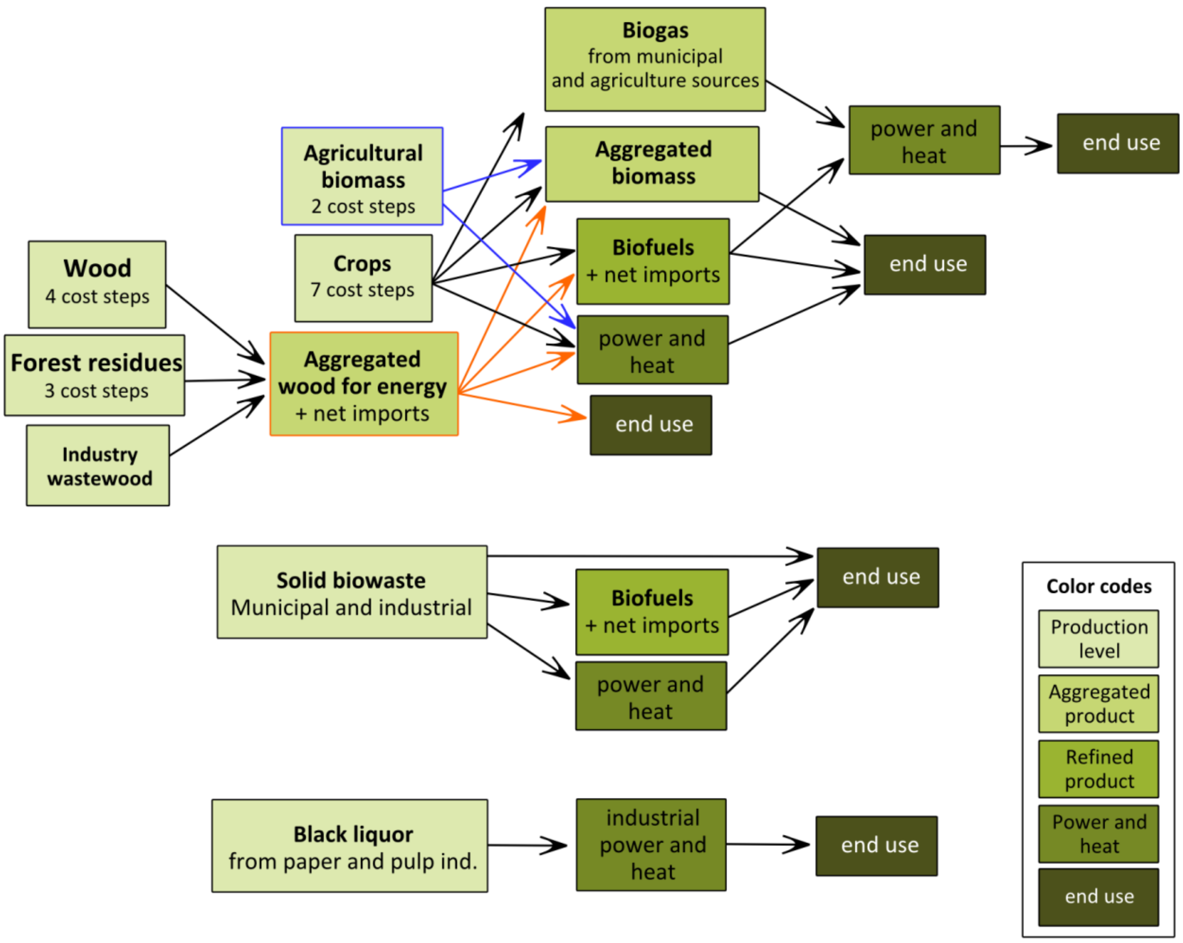

Figure 3.3. Flow chart of biomass in the VTT-TIAM model. The production level is presented with lightest colour, transformation technologies with medium colours and end use with darkest colour.

For this study, the VTT-TIAM model was calibrated to better match the results of the PRIMES Reference 2013 scenario and low-carbon scenario EEMRES30. The population development, GDP drivers and many other assumptions were adopted from PRIMES into VTT-TIAM, to better match the results of the two different models. Usually, different energy system models produce very different results for future development of the European energy system (Knopf *et al.,* 2013). In this study, the differences between VTT-TIAM and PRIMES were relatively small compared to the usual differences.

As explained in Section 3.3, the scenarios were based either on the PRIMES reference 2013 scenario (in the case of the Reference Scenario A), or the PRIMES EEMRES30 scenario (in the case of the decarbonisation scenarios). All scenarios start with the 2020 targets for renewable energy sources and GHG emissions reductions. To prevent unrealistically high imports, the VTT-TIAM model has some settings to put limitations on the import of biomass and biofuels. The annual growth rates for the reference scenario are in line with the PRIMES reference scenario, which projects an increase in the import of solid biomass of 2.2% per year between 2020 and 2050. The import for 2020 is also in line with the expected imports for 2020 as presented by Goh *et al.* (2013). For the scenarios involving relatively high biomass imports (Scenarios B and C1), a maximum annual growth of 5% per year was assumed. In the EEMRES30 scenario, an average annual growth of 3.8% is projected for the import of solid biomass. The historical trend of the importation of wood chips into the EU for the period 2000-2013, based on FAOSTAT data, shows on average an annual increase of 5%. The main parameter settings in the VTT-TIAM model for the different scenarios are described in Table 3.2. Besides these settings, the domestic biomass potentials in the EU are different for each scenario, as explained in Section 3.5.

Biomass potentials for the non-EU regions were derived from the Global Energy Assessment. These potentials are, however, very approximate and uncertain estimates for the main biomass types. These biomass potentials refer to sustainable-yield potentials and also exclude primary forests. The VTT-TIAM model refers to conservative estimates and not the highest estimated potentials.

Table 3.2 Detailed scenario specifications for VTT-TIAM model

Scenarios	Based on following PRIMES scenarios	GHG reduction target and other stimulation measures	RES/Bioenergy targets	Biomass and biofuel import limitations	Forest biomass potentials[1]	Agricultural biomass potentials[2]
A – 'Reference'	PRIMES Reference 2013 scenario	a) GHG -20 % at 2020 b) EU ETS continues with current rules after 2020: annual 1.74 % reduction c) Energy efficiency directive	a) NREAPs at 2020 b) No targets after 2020	Between 2010-2020, annual growth of 7% for biomass and 15% for biofuels and bioliquids. After 2020 annual growth of 2% for solid biomass and biofuels and bioliquids remain at 2020 level	Based on EFSOS II medium mobilisation reference scenario	Based on Biomass Futures reference scenario
B – 'Carry on/ unconstrained use' (no sustainability criteria for solid and gaseous biomass)	Decarbonisation scenario: EEMRES30 (40% GHG and 30% renewable energy sources target for 2030)	a) GHG -20 % at 2020 b) GHG -40 % at 2030 c) GHG -80 % at 2050 d) EU ETS continues with current rules after 2020: annual 1.74 % reduction Additional GHG reductions in the EU ETS are cost optimised d) Energy efficiency directive and additional measures especially in buildings	a) NREAPs at 2020 b) According to the EEMRES30 decarbonisation scenario, with a 30% RES target for 2030. c) No additional renewable energy sources target after 2030. d) After 2020 NREAPs, no additional specific target for biomass	As in Scenario A until 2020 and between 2020-2050 an annual growth of 5%	Based on EFSOS II high mobilisation wood energy scenario	Based on Biomass Futures reference scenario
C1 – 'Carry on/ imported wood' (sustainability criteria for all bioenergy and emphasis on imports)	EEMRES30	As in Scenario B, additional stimulation measures to allow greater amount of bioenergy production and imports	As in Scenario B	As in Scenario B	Based on EFSOS II medium mobilisation reference scenario	Based on Biomass Futures sustainability scenario

Table 3.2 (continued) Detailed scenario specifications for VTT-TIAM model

Scenarios	Based on following PRIMES scenarios	GHG reduction target and other stimulation measures	RES/Bioenergy targets	Biomass and biofuel import limitations	Forest biomass potentials[1]	Agricultural biomass potentials[2]
C2 – 'Carry on/ domestic crops' (sustainability criteria for all bioenergy and emphasis on domestic agricultural biomass)	EEMRES30	As in Scenario B, additional stimulation of dedicated biomass production on marginal/ abandoned lands	As in Scenario B	As in Scenario A	Based on EFSOS II medium mobilisation reference scenario	Based on Biomass Futures sustainability scenario
C3 – 'Carry on/domestic wood' (sustainability criteria for all bioenergy and emphasis on domestic forest biomass)	EEMRES30	As in Scenario B, additional stimulation of bioenergy production from forest resources	As in Scenario B	As in Scenario A	Based on EFSOS II high mobilisation wood energy scenario	Based on Biomass Futures sustainability scenario
D – 'Back off' (sustainability criteria for all bioenergy, but emphasis on other renewable energy sources)	EEMRES30	As in Scenario B	2020 NREAPs are met, but bioenergy target is scaled back after 2020, involving phasing out of large scale biomass technologies and no large scale import of biomass	As in Scenario A until 2020, between 2020-2030 an annual decrease by 5% for biofuels, bioliquids and biomass and after 2030 stable	Based on EFSOS II medium mobilisation reference scenario	Based on Biomass Futures sustainability scenario

Notes to Table 3.2:

1 See Section 3.5 and Appendix 3

2 See Section 3.5 and Appendix 4.

3.4.1. Limitations of the modelling approach

Scenario-based and model-based studies like this one have their limitations due to model simplifications, lack of data and unknown future developments. Some key points are outlined below.

The scenarios developed in this study aim to illustrate the effect of different options related to biomass consumption for bioenergy on GHG emissions, including biogenic carbon emissions. As such, the scenarios are not intended to be a prediction of the future use of biomass for energy and related GHG emissions, since, especially for the longer time scales up to 2050, projections become very uncertain. However, it is one of the specific purposes of this project to investigate the impacts on GHG emissions of different possible paths for the future development of the consumption of biomass for energy. In this context, a prediction of a most likely outcome is of less interest, compared with a range of possible scenarios, as considered in this project. Hence, from the perspective of the consequential LCA study undertaken here, the aim has been to determine a suite of scenarios, each of which represents a set of contrasting actions, which might be adopted in taking forward policies towards bioenergy in the EU. The scenarios should thus illustrate the potential sensitivity of impacts in terms of GHG emissions due to different approaches to encouraging (or indeed discouraging) the use of biomass for energy in the EU.

The scenarios developed using the VTT-TIAM model represent competition between energy sources, but competition for the use of wood in the energy sector and other wood consuming sectors is not represented dynamically in VTT-TIAM. Instead, competition between these sectors is represented explicitly in the input assumptions to VTT-TIAM for each scenario, by referring to results for different EFSOS II scenarios (see Section 3.5.2 and Appendix 3). Whilst this approach was adopted in Task 2, interactions between the energy sector and other wood-using sectors were further explored as part of a sensitivity analysis carried out in Task 3, involving application of the CARBINE model (see Section 4).

As explained in the opening of Section 3.4 and in Appendix 5, the VTT-TIAM model represents the global energy system. As such, the model is able to assess and allow for costs of actions in the energy system (i.e. somewhat wider than just the energy sector), but does not represent all potential costs in other sectors. However, cost estimates for different scenarios are calculated on a common and consistent basis and, as such, are comparable with one another.

Another limitation of the VTT-TIAM model is the limited number of biomass cost steps that can be included. Since VTT-TIAM is a linear optimisation model, it simply chooses the cheapest biomass until the potential is reached, which can lead to an overestimation of a particular biomass source, whilst other sources are not selected, because the average cost is too high.

In undertaking the initial construction of each scenario, particularly when referring to targets for GHG emissions reductions, it was assumed that contributions to GHG emissions from biogenic carbon due to use of bioenergy were zero. Obviously, this assumption does not hold generally and, indeed, may strictly only apply rarely. Whilst contributions to emissions due to biogenic carbon of bioenergy are omitted in the analysis of Task 2, they are fully assessed for each scenario in Task 3. The overall assessment of carbon impacts due to biomass consumption for energy should thus be comprehensive. However, it is important to recognise that, because biogenic carbon emissions are assessed subsequently to the development of scenarios in Task 2, in practice, the GHG emissions reductions targets specified for each scenario in VTT-TIAM are unlikely to be met. Whilst this does not invalidate the scenarios or the subsequent assessment of GHG emissions (indeed, it is precisely the purpose of this project to identify and understand such impacts), ideally, the original VTT-TIAM scenarios should be re-run after the calculation of the additional biogenic carbon emissions in Task 3. However, such iterative steps to refine the scenarios were beyond the scope of this project.

3.5. Assumptions on biomass potentials

As explained earlier in this section, scenario results for biomass potentials developed by the Biomass Futures (Elbersen *et al*., 2012, 2013) and EFSOS II (UNECE and FAO, 2011) studies were referred to in developing the scenarios in Task 2. Further details of these studies and the estimated potentials are given in Appendix 2, Appendix 3 (EFSOS II) and Appendix 4 (Biomass Futures). As already noted, the number of biomass classes and cost steps in VTT-TIAM is limited, whilst Biomass Futures and EFSOS II results give more detailed information for some of the biomass categories. Hence, the biomass potentials and costs were aggregated into the classes described in Table 3.3. For these classes, the biomass potentials and costs were determined for each scenario. Data at Member State level were aggregated into the five EU regions represented in VTT-TIAM (Western EU, Eastern EU, Denmark, Sweden and Finland). Further details are provided in the following discussion. For all biomass types, the biomass potentials for 2010 and 2020 are the same for all scenarios, and start deviating according to the scenario specifications after 2020.

Table 3.3 Biomass potential and cost classification for VTT-TIAM

VTT-TIAM biomass class	Step	Biomass classification	Explanation
Crops	Step 1	Woody crops	Perennial woody energy crops, cost class 1
Crops	Step 2	Woody crops	Perennial woody energy crops, cost class 2
Crops	Step 3	Grassy crops	Perennial grassy energy crops, cost class 1
Crops	Step 4	Grassy crops	Perennial grassy energy crops, cost class 2
Crops	Step 5	Biodiesel crops	Annual crops (rapeseed, sunflower)
Crops	Step 6	Bioethanol crops	Annual crops (cereals, maize and sugarbeet)
Crops	Step 7	Biogas crops	Fodder maize
Wood	Step 1	Firewood	Current traditional firewood use
Wood	Step 2	Stemwood	Stemwood potential for energy, cost class 1
Wood	Step 3	Stemwood	Stemwood potential for energy, cost class 2
Wood	Step 4	Stemwood	Stemwood potential for energy, cost class 3
Forest residues	Step 1	Forest residues 1	Forest residues, cost class 1
Forest residues	Step 2	Forest residues 2	Forest residues, cost class 2
Forest residues	Step 3	Forest residues 3	Forest residues, cost class 3
Agricultural residues	Step 1	Agricultural wood	Prunings and landscape care wood
Agricultural residues	Step 2	Straw	Straw (from cereals, sunflower and rapeseed)
Manure	Step 1	Liquid manure	Liquid manure for anaerobic digestion
Manure	Step 2	Solid manure	Solid manure for anaerobic digestion

3.5.1. Agricultural biomass potentials

Agricultural biomass comprises all biomass from the agricultural sector, both crops (annual and perennial energy crops) and residues (crop residues and manure). For biomass from agriculture, the potentials are mainly based on the Biomass Futures study (see Appendix 4). The study quantified regional biomass potentials and costs for a range of biomass types, for a 'reference' and 'sustainability' scenario, and produced maps with the biomass potentials for a range of biomass sources (Elbersen *et al*., 2012, 2013).

The biomass potential from arboricultural arisings (otherwise referred to as landscape care wood), as used in Biomass Futures, was directly based on the national values derived by the EUwood study (Mantau *et al*., 2010). However, for some of the biomass categories, more recent data are now available, and/or the assumptions from Biomass Futures are not in line with this project. Hence, the potentials for annual biofuel crops and for manure were updated, as explained in the ensuing discussion. As the biomass potentials from Biomass Futures are mainly technical potentials, assumptions were made about the available potential for energy for the respective scenarios, which should be in line with the scenario storylines. The assumptions for the agricultural biomass sources are presented in Table 3.4.

For the annual biofuel crops, the potentials based on the EU agricultural outlook (European Commission, 2013) were updated, since the values from Biomass Futures were derived from CAPRI (Common Agricultural Policy Regionalized Impact) data (Britz and Witzke, 2012) that were directly linked to the predicted biofuel demand from previous PRIMES scenarios. In theory, the potential for annual biofuel crops could be very high, since the market and policy restrictions determine whether these crops are used for food, feed or biofuel production. Hence, it was decided to scale the Biomass Futures potentials to the 2020 EU total for domestic (first generation) biofuels, as projected in the most recent EU agricultural outlook (European Commission, 2013). This outlook study projects the highest biofuel production by 2020 followed by a slight decrease (Figure 3.4).

Table 3.4 Assumptions underlying biomass potentials from agriculture for 2030

Scenarios	Perennial energy crops	Annual energy crops	Straw	Agri-wood (prunings and arbori-cultural arisings)	Manure
A – 'Reference'	10% of potential from Biomass Futures reference scenario	60% of Biomass Futures potential for bioethanol crops and 50% for biodiesel crops assumed to be mainly derived from co-production and 100% for biogas crops.	50% of Biomass Futures reference scenario	50% of Biomass Futures reference scenario	All available pig and cattle manure from farms with > 200 livestock units
B – 'Carry on/ unconstrained use'	100% of potential from Biomass Futures reference scenario	60% of Biomass Futures potential for bioethanol crops and 50% for biodiesel crops assumed to be mainly derived from co-production and 100% for biogas crops.	100% of Biomass Futures reference scenario	100% of Biomass Futures reference scenario	All available pig and cattle manure from farms with > 200 livestock units
C1 – 'Carry on/imported wood'	25% of potential from Biomass Futures sustain-ability scenario	60% of Biomass Futures potential for bioethanol crops and 50% for biodiesel crops assumed to be mainly derived from co-production and 25% for biogas crops.	75% of Biomass Futures sustainability scenario	75% of Biomass Futures sustainability scenario	75% of all available pig and cattle manure from farms with > 100 livestock units
C2 – 'Carry on/domestic crops'	100% of potential from Biomass Futures sustain-ability scenario	60% of Biomass Futures potential for bioethanol crops and 50% for biodiesel crops assumed to be mainly derived from co-production and 25% for biogas crops.	100% of Biomass Futures sustainability scenario	100% of Biomass Futures sustainability scenario	All available pig and cattle manure from farms with > 100 livestock units
C3 – 'Carry on/ domestic wood'	40% of potential from Biomass Futures sustain-ability scenario	60% of Biomass Futures potential for bioethanol crops and 50% for biodiesel crops assumed to be mainly derived from co-production and 25% for biogas crops.	75% of Biomass Futures sustainability scenario	100% of Biomass Futures sustainability scenario	All available pig and cattle manure from farms with > 100 livestock units
D – 'Back off'	5% of potential from Biomass Futures sustain-ability scenario	No annual biofuel and biogas crops	25% of Biomass Futures sustainability scenario	50% of Biomass Futures sustainability scenario	50% of all available pig and cattle manure from farms with > 100 livestock units

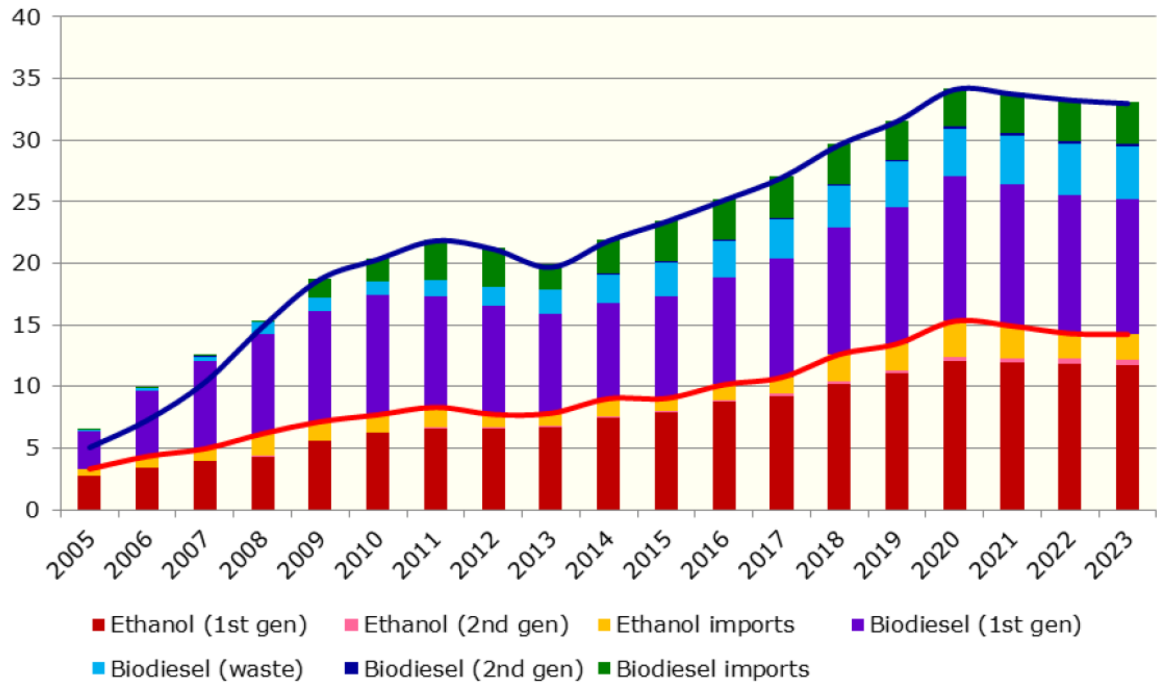

Figure 3.4. EU biofuel consumption by source in Mtoe (Source: European Commission, 2013).

For all of the scenarios developed, lower biomass potentials for the food-based biofuel crops, after 2020, were referred to. This follows the EC decision not to allow for national or European support to food-based biofuels after 2020. However, for this project, the view was taken that a complete reduction is not realistic, as some of the current biofuel plants will remain in production. Moreover, if crops are not only used for biofuel production, but also for other kinds of biorefinery concepts, i.e. extraction of compounds for materials and chemicals, the GHG balance is likely to be more favourable, and biofuels can be produced from the remaining biomass. Also, the EU agricultural outlook showed only a limited decrease in first generation biofuel crops after 2020. Hence, the potentials for annual bioethanol crops were set at 60%, and for biodiesel crops were set at 50%, of the 2030 potentials of the Biomass Futures sustainability scenario. These 2030 potentials are already lower than the 2020 potentials, which effectively lead to about a 50% lower potential for bioethanol crops and about a 75% lower potential for biodiesel crops for 2030 and onwards. For biodiesel, a stronger reduction is expected, since these crops often have lower GHG savings and potentially high impacts in terms of iLUC. Only for Scenario D (‘Back off’), was it assumed that food crops are no longer used for biofuel production, thus the potentials for bioethanol and biodiesel crops are set at zero. For biogas crops (i.e. silage/energy maize) the sustainability criteria of the Renewable Energy Directive do not apply, since these only refer to biofuels and bioliquids. Hence, these crops have a higher potential in Scenarios A and B (100% of the Biomass Futures potential), compared with the other scenarios (25% of the Biomass Futures sustainability scenario).

Finally, the energy potential for manure was changed, based on new potentials for biogas. The potentials were derived from MITERRA-Europe data (Velthof *et al.,* 2009), taking account of the available amount of manure and farm size. The total amount of manure potentially available for anaerobic digestion was calculated, based on animal numbers, excretion factors, grazing time and manure storage system. Next, it was assumed that anaerobic digestion of manure for biogas would only occur on larger farms, since it will not be cost-effective for small amounts of manure. It was estimated that current farm scale anaerobic digestion would require a manure input of at least about 200 livestock units (LSU). Based on Eurostat FSS data on farm size, expressed in terms of LSU per farm, the amount of manure available was estimated for farms with more than 200 LSU within each NUTS2 region. Cattle and pig manure were included and a distinction was made between liquid and solid manure. Liquid manure is currently most commonly used for anaerobic digestion; solid manure could be used, but requires an additional processing step. Hence, a slightly higher cost was assumed for solid manure.

In the decarbonisation scenarios, it was assumed that manure from smaller farms (>100 LSU) would also be available for anaerobic digestion, due to stimulation measures. Since manure storage is a source of CH_4 and N_2O emissions, anaerobic digestion can be considered as mitigation measure, which is in line with more strict sustainability criteria. The incineration of manure was not included in estimates of potentials, although this is practiced for poultry manure in a few countries, e.g. the United Kingdom and the Netherlands. Manure incineration cannot be considered as a very sustainable practice, since all nitrogen and carbon is lost, which should then be replaced by mineral fertilizer and/or other organic inputs. Hence, manure incineration might occur only in some countries/regions with manure surpluses, but will remain small compared to other biomass sources.

3.5.2. Forest biomass potentials

Forest biomass comprises all biomass from the primary forestry sector, including harvested stemwood and harvest residues (including branchwood and stumps). Waste from the forest industry is included under waste biomass (see later in this discussion). As explained in the Glossary to this report, there is no international standard definition for stemwood. However, in practice, definitions used in different countries and for different types of trees are generally very similar. For example, in the UK (Forestry Commission, 2011), the definition of stemwood is given as, "The woody material forming the above ground main growing shoot(s) of a tree or stand of trees. The stem includes all woody volume above ground with a diameter greater than 7 cm over bark. Stemwood includes wood in major branches where there is at least 3 m of 'straight' length to 7 cm top diameter".

Potentials for biomass from forests were based on those in the European Forest Sector Outlook Study II (EFSOS II; UNECE and FAO, 2011), which builds further on the EUwood study (Mantau *et al*., 2010). EFSOS II comprises the latest data and has a more elaborated scenario analysis compared to the EUwood study. In EFSOS II, the EFISCEN model was used to assess the realisable harvest potentials for the period 2010-2030 with five-year time-steps, as input to the EFI-GTM forest sector model. Several scenarios were developed by the EFSOS II study, and those relevant to this study were the 'reference' scenario and the 'wood energy' scenario. In these scenarios, the forest area available for wood supply remains the same, thus it is assumed that areas currently classified as not available for wood supply remain as such, and no harvesting from these areas is included in estimates of potentials. In the wood energy scenario, absolute priority is given to meeting the policy targets for renewable energy, which leads to an increase of the total wood supply of 22% (250 million m^3) compared to the reference scenario. According to the EFSOS II scenario, the largest increase would come from the extraction of harvest residues and stumps.

Potentials were estimated separately for:

- Stemwood
- Branchwood
- Stumps and coarse roots
- Harvest residues other than branchwood, stumps and coarse roots
- Woody biomass from early thinnings in young forests.

The potential supply was estimated based on an approach developed by Verkerk *et al.* (2011) in the EUwood study. Firstly, the theoretical potential of forest biomass supply in Europe was estimated based on detailed forest inventory data. Secondly, multiple environmental, technical and social constraints were defined and quantified that reduced the amount of biomass that can be extracted from forests for three differently-defined scenarios for future wood mobilisation (low, medium and high). Thirdly, the theoretical potentials from the first step were combined with the constraints from the mobilisation scenarios. The high and medium mobilisation scenarios were referred to for the purposes of this current study.

The EFSOS II dataset also provides information on the current supply of firewood for traditional consumption. It was assumed that this amount of wood should remain available for energy production in all scenarios, at a relatively low cost (set at 2 €/GJ). The remaining potential of stemwood for energy is based on the EFSOS II study, by combining the potentials for wood supply estimated using EFISCEN with the estimates of wood demand produced by the EFI-GTM model. The remaining potential of stemwood for energy is calculated by subtracting the total demand from the wood industry (chemical pulp, mechanical pulp, sawn wood, panels and plywood) from the total wood supply (domestic harvest, post-consumer wood, sawmill and plywood residues, other industrial residues, black liquor, bark and imported wood). Table 3.5 provides an overview of the assumptions referred to in the estimation of the forest-based biomass potentials.

For the purposes of this project, estimates of potential for harvest residues excluded the extraction of stumps and rots, since this practice can have significant negative impacts on soil carbon and biodiversity (Walmsley and Godbold, 2010; Pedroli *et al.*, 2013). However, it should be noted that stump harvesting is already occurring in some countries, although currently on a small scale.

Table 3.5 Assumptions underlying forest biomass potentials

Scenarios	Traditional firewood	Stemwood	Forest residues
A – 'Reference'	Current supply for all years based on EFSOS II data	Remaining stemwood potential (having allowed for demand in other sectors) from EFSOS II medium mobilisation scenario	Primary forest residue potential from EFSOS II medium mobilisation scenario
B – 'Carry on/ unconstrained use'	Current supply for all years based on EFSOS II data	Remaining stemwood potential from EFSOS II high mobilisation scenario	Primary forest residue potential from EFSOS II high mobilisation scenario
C1 – 'Carry on/ imported wood'	Current supply for all years based on EFSOS II data	Remaining stemwood potential from EFSOS II medium mobilisation scenario	Primary forest residue potential from EFSOS II medium mobilisation scenario
C2 – 'Carry on/ domestic crops'	Current supply for all years based on EFSOS II data	Remaining stemwood potential from EFSOS II medium mobilisation scenario	Primary forest residue potential from EFSOS II medium mobilisation scenario
C3 – 'Carry on/ domestic wood'	Current supply for all years based on EFSOS II data	Remaining stemwood potential from EFSOS II high mobilisation scenario	Primary forest residue potential from EFSOS II high mobilisation scenario
D – 'Back off'	Current supply for all years based on EFSOS II data	25% of remaining stemwood potential from EFSOS II medium mobilisation scenario	Primary forest residue potential from EFSOS II medium mobilisation scenario

3.5.3. Waste biomass potentials

Waste is also an important biomass source, but this project is concerned primarily with impacts related to biogenic carbon of primary biomass sources. Biomass waste is represented in the VTT-TIAM model, but estimates of waste biomass potentials referred to by the model were not further elaborated for the purposes of this project. The waste biomass category consists of industrial waste wood, solid biowaste and waste gas. The amount of solid biowaste and waste gas was calibrated to the PRIMES Reference 2013 scenario or the EEMRES30 scenario, as appropriate. In this study, the VTT TIAM model chose the most cost-effective way to utilise the waste, based on the scenario targets, constraints and the availability of the other biomass sources.

The amount of waste wood from industry is calculated internally in the VTT-TIAM model based on the amount of wood going to the industry sector. The quantities of wood for industry and industrial waste wood for energy at 2010 were calibrated according to the EFSOS II study (see Appendix 3). The quantities of wood supplied to wood-using industries other than energy are the same for all scenarios, but the amount of wood waste can differ for the scenarios, depending on prices and technology pathways.

Possible transformation technologies for waste biomass include power and heat, ethanol production, small scale combustion and anaerobic digestion for biogas production.

3.5.4. Final biomass potentials

As described in the preceding discussion in this section, detailed data on biomass potentials are available for 2010, 2020 and 2030 from the main sources (i.e. Biomass Futures and EFSOS II). However, beyond 2030 there is very limited data available on biomass sources, potentials and costs. There are studies which have assessed energy scenarios up to 2050 or further, e.g. the Energy Roadmap 2050, the Global Energy Assessment and the IEA Bioenergy Technology Roadmap (see Appendix 2). However, these only provide data at aggregated levels with respect to spatial resolution (mainly at EU level and not at Member State level) and types of biomass (often just one aggregated biomass class).

For most biomass types, it was assumed that the potential in 2050 is equal to 2030. For forest bioenergy, there is some scope to increase the potential, but this is limited, even up to 2050, as most forests grow slowly and new afforested land can require decades to become productive. Ericsson and Nilsson (2006) showed that the potential remains fairly constant for the period from 2030 to 2040. Furthermore, for agriculture, there is no forecast suggesting that the agricultural area will significantly expand in the European Union. Most studies (e.g. Alexandratos and Bruinsma, 2012) project a decline in agricultural land for the EU. This means that the potential use of agricultural residues is very unlikely to increase. For perennial energy crops only, an increase in yield of 20% over the period from 2030 to 2050 was assumed in those scenarios that were developed based on results from the Biomass Futures sustainability scenario (i.e. Scenarios C1, C2, C3 and D), due to investments in better technologies and improved cultivars.

Figure 3.5 and Table 3.6 show the estimated biomass potentials for the EU27 region for the six scenarios for different years.

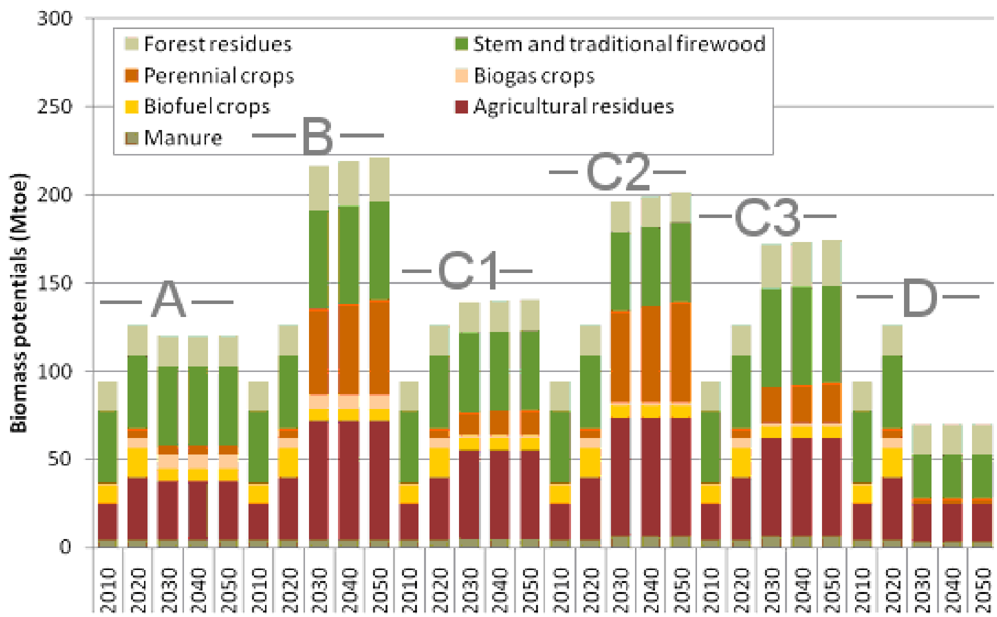

Figure 3.5. Biomass potentials and sources for bioenergy in the EU27 under different scenarios.

The total biomass potential is highest in Scenario B, since both the forest and agricultural potentials are fully available with few constraints. The biomass potential is higher in the agriculture-focussed Scenario C2, compared with the forest bioenergy-focussed Scenario C3, mainly because the domestic potential for perennial energy crops is larger than the potential from EU forests. The full potential of agricultural residues and manure is available for energy production in Scenario C2. Scarlat *et al*. (2010) made a detailed assessment of the potential of crop residues for energy, and an EU27 average was estimated at 36.5 Mtoe (1530 PJ) per year, which is in line with the estimates in this project of 24 Mtoe (1000 PJ) in 2030 for Scenario A, and 48 Mtoe (2000 PJ) for Scenarios B and C2.

Table 3.6 Biomass potentials in the EU27 under different scenarios over the period 2010 to 2050

Scenario	Year	Biomass potential (Mtoe yr^{-1})						
		Manure	Agricultural residues	Biofuel crops	Biogas crops	Perennial crops	Stem and traditional firewood	Harvest residues
A	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
A	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
A	2030	4.2	33.9	6.6	7.9	4.9	45.0	17.3
A	2040	4.2	33.9	6.6	7.9	4.9	45.0	17.3
A	2050	4.2	33.9	6.6	7.9	4.9	45.0	17.3
B	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
B	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
B	2030	4.2	67.7	6.6	7.9	49.2	55.4	25.5
B	2040	4.2	67.7	6.6	7.9	51.7	55.4	25.5
B	2050	4.2	67.7	6.6	7.9	54.2	55.4	25.5
C1	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
C1	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
C1	2030	4.9	50.5	6.6	2.0	12.9	45.0	17.2
C1	2040	4.9	50.5	6.6	2.0	13.6	45.0	17.2
C1	2050	4.9	50.5	6.6	2.0	14.2	45.0	17.2
C2	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
C2	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
C2	2030	6.5	67.3	6.6	2.0	51.6	45.0	17.3
C2	2040	6.5	67.3	6.6	2.0	54.2	45.0	17.3
C2	2050	6.5	67.3	6.6	2.0	56.8	45.0	17.3
C3	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
C3	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
C3	2030	6.5	55.5	6.6	2.0	20.6	55.4	25.5
C3	2040	6.5	55.5	6.6	2.0	21.7	55.4	25.5
C3	2050	6.5	55.5	6.6	2.0	22.7	55.4	25.5
D	2010	4.2	20.7	10.8	1.1	0.0	40.4	16.8
D	2020	4.2	35.4	16.6	5.5	5.8	41.6	17.1
D	2030	3.3	21.8	0.0	0.0	2.6	24.9	17.3
D	2040	3.3	21.8	0.0	0.0	2.6	24.9	17.3
D	2050	3.3	21.8	0.0	0.0	2.6	24.9	17.3

3.6. Assumptions on biomass costs

There is quite limited information available on biomass costs. Cost data are available for some biomass types that are already widely used commodities for energy, e.g. biofuel crops and wood. However, these costs often largely depend on market prices, which can be highly volatile and difficult to predict. For other biomass types, such as perennial energy crops, no large market for energy has developed yet, and most data come from case studies where costs of production have been estimated. Hence, the main source of cost data referred to was from the Biomass Futures project, for which results were scaled to represent 2010 values. However, the Biomass Futures cost data mainly refer to the direct cost of the biomass, and do not include the costs of transport and processing (e.g. pelletising). The cost estimates were, therefore, increased for some of the biomass types (i.e. perennial energy crops, straw and arboricultural arisings/agricultural wood), to allow for these costs. An additional cost step was added for woody energy crops and energy grasses, to improve their representation in the VTT-TIAM model, as otherwise all the potential biomass of these crops would be either completely used or completely unused in the linear optimisation. To achieve this, the average costs for these biomass types were adjusted, such that half of the biomass potential was assumed to be available at 10% below the average cost in 2020, whilst the other half was assumed to be available at 10% above the average cost. (This had the effect of keeping the average cost unchanged.) For 2030 and onwards, the adjustment was 30% below and above the average cost. Few cost data were available for manure. It was assumed that farm-scale anaerobic digestion of the manure itself has almost negligible costs, whilst the main costs are in the equipment. The VTT-TIAM model allows for these technology costs, therefore relatively low costs of 2 €/GJ were assumed for liquid manure, whilst 3 €/GJ was assumed for solid manure, for all countries and scenarios.

For stemwood costs, reference was made to the EFI-GTM data from the EFSOS II study. This study provided (modelled) cost data for coniferous and non-coniferous pulp and sawlog wood for 2010, 2020 and 2030, at country scale, for the reference and wood energy scenarios of EFSOS II. Based on pulpwood cost data, and the ratio of potentials for coniferous and non-coniferous wood, derived from the EUwood study, an average cost for stemwood for energy was calculated. To improve the representation of stemwood costs in the VTT-TIAM model, several cost steps were included for stemwood, to better represent the lower-end and higher-end costs of biomass. The average costs of stemwood derived from the EFSOS II study were adjusted, such that 30% of the stemwood potential was assumed to be available at 15% below the average cost in 2020, 40% was assumed to be available at the average cost, whilst 30% was assumed to be available at 15% above the average cost. (This had the effect of keeping the average cost unchanged.) For 2030 and onwards the adjustment for lower and higher costs was changed from 15% to 30%.

A different source of data was referred to in estimating the costs of forest harvest residues. This was necessary because the Biomass Futures study only considers one category with one cost level, whilst the EFSOS II study does not provide any cost data for harvest residues. In EEA (2007), three cost levels for primary forest harvest residues were distinguished, with a related biomass potential reported for each class at national scale. The relative share of biomass potential in each cost class was derived from this study, and these results were multiplied by the latest estimates of potentials for forest harvest residues, as reported by the EFSOS II study.

For traditional firewood, no cost data are available, since it is not part of the large-scale commercial wood commodity market, but instead is generally supplied at small and local scale by private forest owners. Hence, a fixed low cost of 2 €/GJ was assumed to ensure that all this biomass would be used in the model.

Figure 3.6 shows the average costs for the different biomass types supplied from within the EU27 region, for each of the VTT-TIAM sub-regions for 2030. As explained above, these cost estimates were derived from a combination of the Biomass Futures and EFSOS II projects, augmented with estimates from EEA (2007). The cost for stemwood is much higher compared with traditional firewood, because of the competition with other wood uses in the case of stemwood. These average biomass costs were used in the development of all scenarios, subject to the adjustments to represent cost steps, as described above. Cost estimates in 2030 are higher than for 2010, and cost estimates for the highest cost steps are significantly higher than for other energy feedstocks.

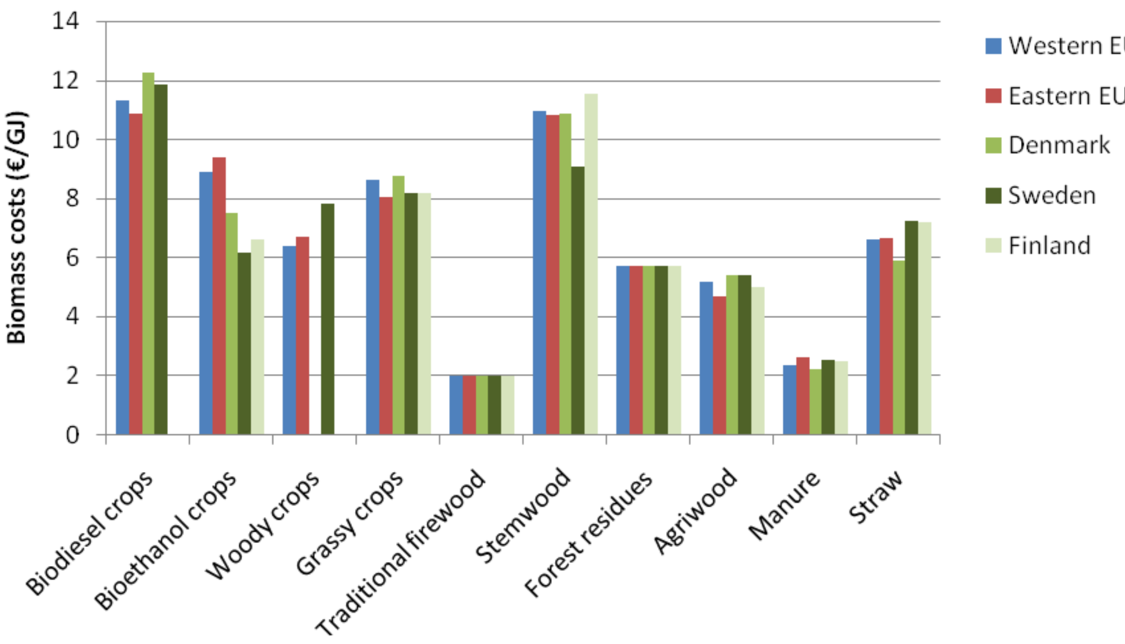

Figure 3.6. Average biomass costs for 2030 (at 2010 prices) by biomass type and region.

Figure 3.7 shows the cost-supply curves for biomass supplied from within the EU27 region, for all biomass at EU level, for the six scenarios. The estimated costs of biomass for the high levels of biomass supply represented in Figure 3.7 are very much more expensive than 2010 costs, and also much higher than the costs of other energy feedstocks. This reflects, amongst other factors, the costs of infrastructure development to supply the high levels of biomass represented in the high-bioenergy scenarios.

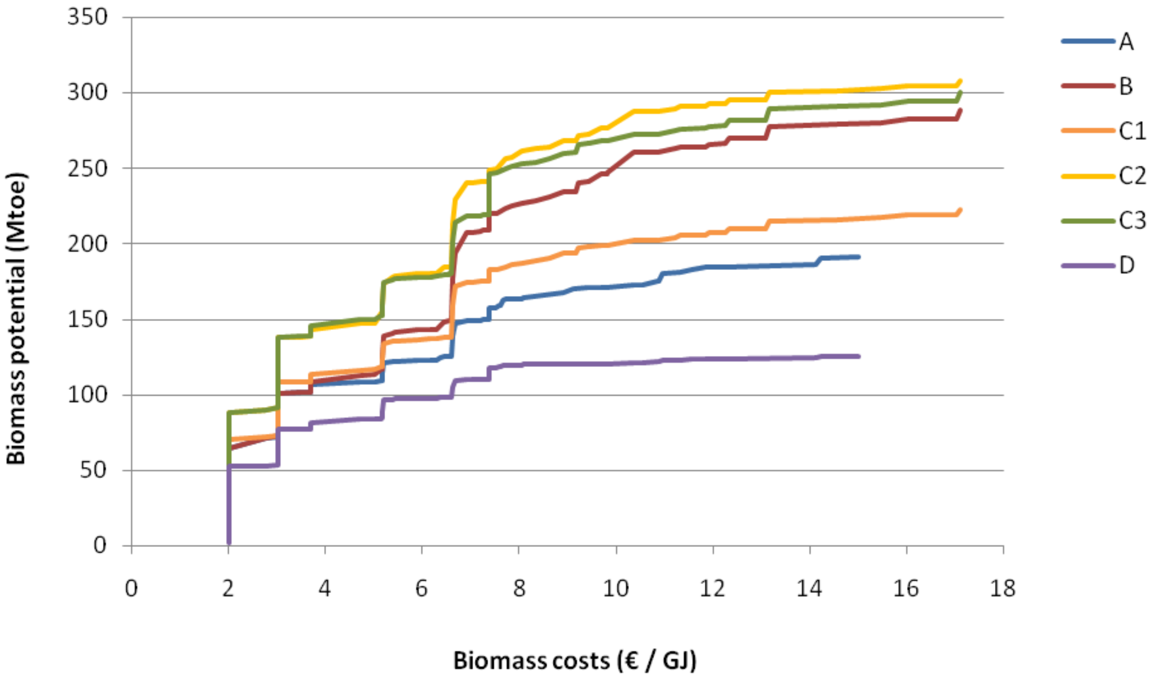

Figure 3.7. EU27 domestic biomass cost-supply curves for 2030, for the different scenarios developed in this project (based on 2010 prices).

3.7. Main results for scenarios

The VTT-TIAM model was used to simulate the supply and consumption of biomass for energy for the six scenarios defined in this project, based on the settings and assumptions made for the different scenarios, and the associated biomass potentials and costs, as described earlier in this section. The main results of this modelling exercise are presented in this section. The results considered here are aggregated at EU scale. More details for these results can be found in Appendix 6. Results were also produced for the five EU regions represented in VTT-TIAM (Western Europe, Eastern Europe, Denmark, Sweden and Finland), which were used to further downscale the relevant outputs to the scale of individual Member States, as required for the assessment of some aspects of the biogenic carbon and non-biogenic GHG emissions impacts of biomass use. The VTT-TIAM model also produces detailed results on biomass and energy conversion technologies, which have been referred to in the analysis of indirect GHG emissions undertaken in Task 4 of this project.

The VTT-TIAM model provides a range of possible output indicators. Results for the most relevant indicators, as calculated for the six scenarios developed in this project, are presented in Sections 3.7.1 to 3.7.3.

3.7.1. Energy supply and consumption

Figure 3.8 shows results for the total primary energy supply in the EU27. The total is about the same for all scenarios, but the share due to (i.e. the contribution made by) bioenergy differs. For the Reference Scenario A, the share of bioenergy (biomass, bioliquids and biogas) increases from 5.5% in 2010 to 9.7% in 2050, whilst in the various high-bioenergy scenarios (Scenarios B, C1, C2 and C3), the share increases to between 17.0 and 21.4% by 2050. For Scenario D ('Back off') the bioenergy share is 7.9% by 2050, but this is compensated for by a higher share of other renewable energy sources (wind, solar, hydro, geothermal) and nuclear energy. For 2030, the lower use of biomass in Scenario D is mainly compensated for by higher use of wind energy (1.3 times higher in 2050 compared with 2010) and solar energy (2.9 times higher).

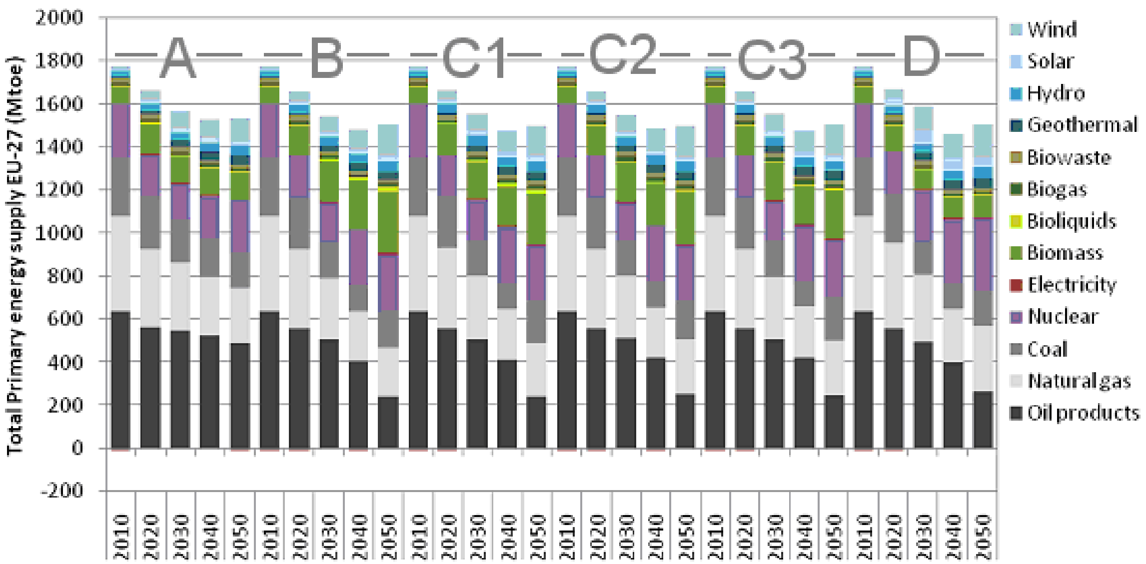

Figure 3.8. Total primary energy supply in the EU27 for the different scenarios developed in this project.

Figures 3.9a and 3.9b show the final energy consumption in the EU27 from bioenergy sources, by sector for the six scenarios developed in this project. The results of the VTT-TIAM model for the contribution of bioenergy to final energy consumption can be disaggregated into two broad categories:

1 Biomass, bioliquids, and biogas (these sources are predominantly composed of biomass obtained from agriculture, forests and other primary sources; biofuels that can be used to displace liquid fuels derived from fossil fuels; biomethane and synthetic natural gas produced by a number of different processes from a variety of different types of biomass)
2 Heat and power consumed as final energy in various sectors, but generated industrially from biomass.

Results for these two broad categories are shown, respectively, in Figures 3.9a and 3.9b. The two categories of bioenergy defined above both make a significant contribution to final energy consumption from bioenergy in all scenarios.

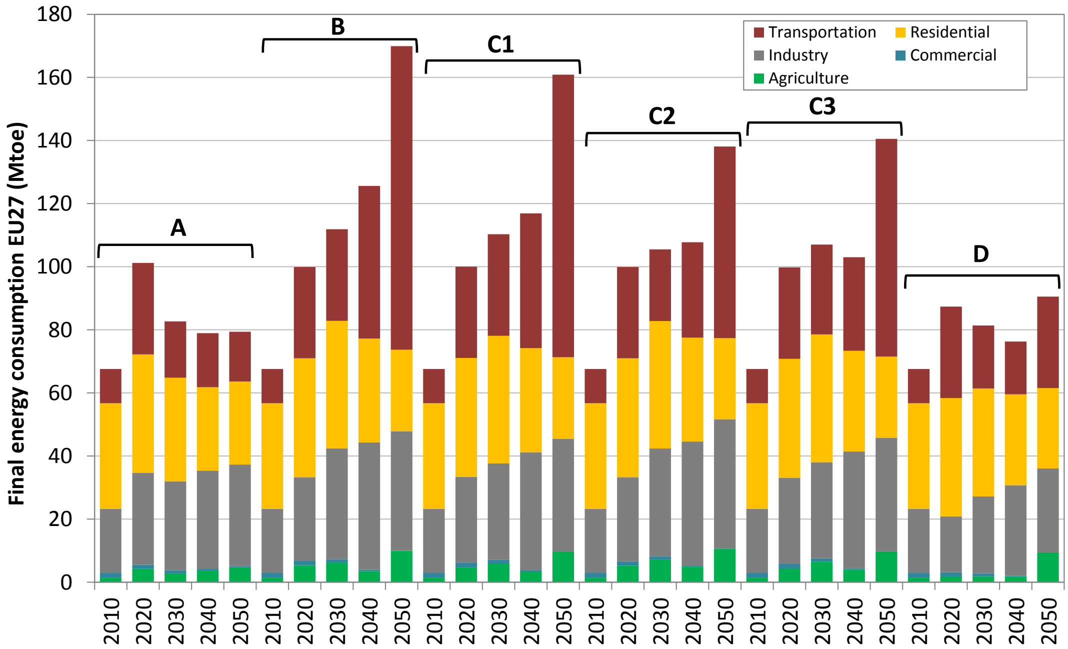

Figure 3.9a. Final energy consumption of biomass, bioliquids and biogas, by sector in the EU27 for the different scenarios developed in this project.

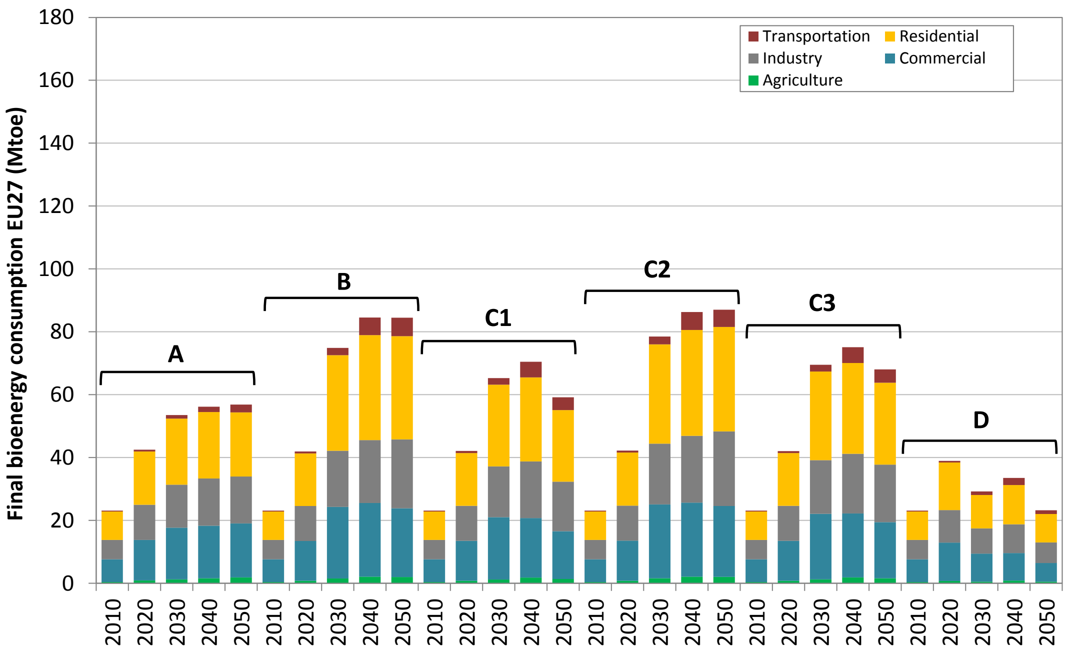

Figure 3.9b. Final energy consumption of heat and power generated industrially from biomass, by sector in the EU27 for the different scenarios developed in this project.

For the year 2030, the projected relative contribution towards total final energy consumption from bioenergy sources, due to biomass, bioliquids and biogas on the one hand, and due to heat and power generated industrially from biomass on the other hand, is roughly 60:40 in all scenarios, with the exception of Scenario D (75:25).

Overall, total final energy consumption from bioenergy sources is highest for Scenarios B and C1, which means that limits on biomass imports, as included in Scenarios C2 and C3, lead to lower bioenergy consumption, and that the availability of biomass within the EU region is not sufficient to satisfy the demand for bioenergy represented in Scenarios B and C1. The use of biofuels in the transport sector is notably higher in Scenarios B and C1 after 2020. Final energy consumption is also reported by fuel type for the different sectors represented in the VTT-TIAM model (agriculture, commercial, industry, residential and transportation). This can be even further subdivided for each sector, for example, for the residential sector, into space heating, water heating, cooking and 'other'. These details are not provided in this report, but are of relevance for Task 4, in which the indirect GHG emissions of entire energy pathways are assessed for the different sources of solid biomass.

Figures 3.10 and 3.11 show, respectively, the share of (i.e. the contribution towards) final energy consumption due to renewable energy sources, and due specifically to biomass. All the decarbonisation scenarios reach the 2030 target for renewable energy consumption of 30%, whilst in the Reference Scenario A, the share due to renewable energy remains at 25%. After 2030, the renewable energy share increases further in the decarbonisation scenarios, to about 45% by 2050. The biomass share increases from ~13% in 2020 up to ~27% in 2050 in the high-bioenergy scenarios (Scenarios B, C1, C2 and C3), whilst it stays at ~14% for the low scenarios (Scenarios A and D).

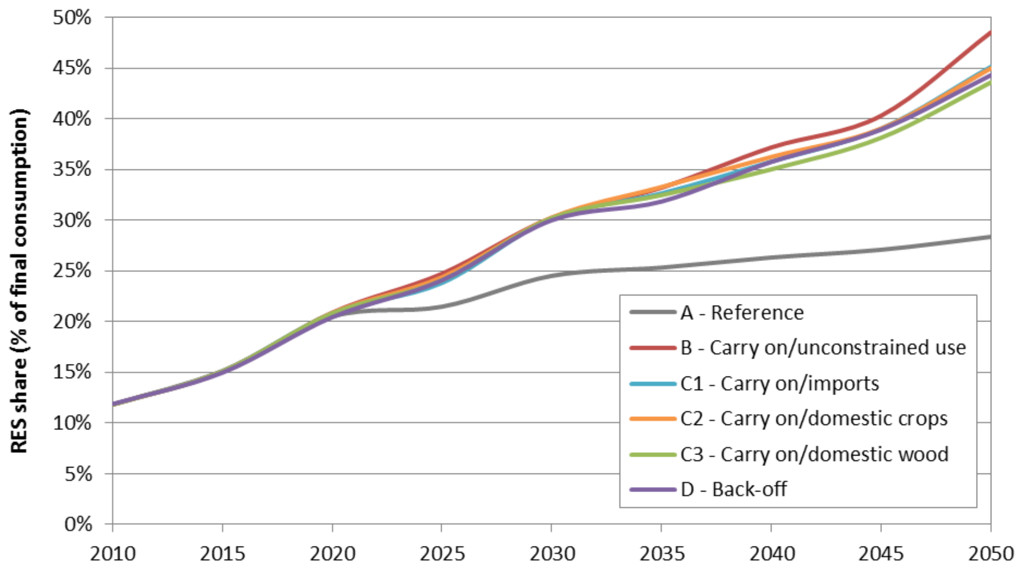

Figure 3.10. Renewable energy share of final energy consumption in the EU27 for the different scenarios developed in this project.

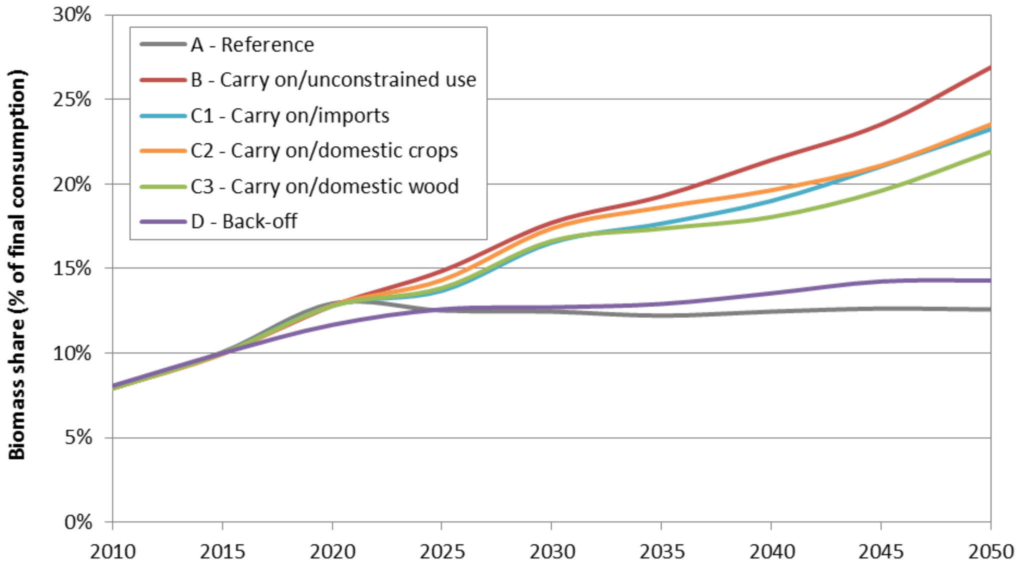

Figure 3.11. Biomass share of final energy consumption in the EU27 for the different scenarios developed in this project.

3.7.2. Biomass supply

Based on the scenario settings and assumptions, the specified demand for total energy and bioenergy, and estimates of potentials and costs for biomass sources, the VTT-TIAM model calculates the amount of biomass supplied from different sources, and differentiates between domestic production and imports. Table 3.7 shows a summary of projected biomass supply from different sources in 2030 for the scenarios developed in this project.

Note that the scenarios developed in this project, based on the simulations of the VTT-TIAM model, also include projections of energy supplied from waste biomass sources (referred to as biowaste and biogas). Results for these are not included in Table 3.7, which is concerned with the supply of biomass from primary sources. It should also be noted that projections of biomass supply to the EU27 region, as made by the VTT-TIAM model, include a contribution from the supply of black liquor (a by-product of paper manufacture). Contributions due to black liquor are not shown in Table 3.7, which focuses on primary sources of biomass supply. The contribution to biomass supply made by black liquor is similar in all scenarios, at between 13 and 14 Mtoe.

Generally, the contributions made by different sources of biomass to total biomass supply follow the definitions specified for the various scenarios developed in this project.

Total biomass supply in 2030 (from all sources) is highest in Scenarios B and C2, at about 170 Mtoe, and somewhat lower in Scenarios C1 and C3, at 154 and 159 Mtoe, respectively.

Table 3.7 Projected primary biomass supply from different sources in 2030 by scenario

Biomass source	Biomass supply in 2030 (Mtoe)					
	A	**B**	**C1**	**C2**	**C3**	**D**
Agricultural biomass from EU27 region	42	93	68	102	75	24
Forest biomass from EU27 region	49	47	54	47	65	43
Total biomass from EU27 region	**92**	**140**	**122**	**149**	**140**	**67**
Total imported forest biomass	19	32	32	19	19	10
Total biomass supply	**110**	**172**	**154**	**168**	**159**	**77**

Note that, if the contribution due to black liquor is allowed for, the total supply of biomass (as defined in the VTT-TIAM model) in 2030 under Scenarios B and C2 is 183 Mtoe; for Scenario C1, the total biomass supply including black liquor is 168 Mtoe, whilst for Scenario C3 the equivalent result is 173 Mtoe.

For Scenarios B and C2, agricultural biomass produced in the EU27 region contributes about 100 Mtoe, nearly 70% of biomass supplied domestically from within the EU27 region (not including black liquor), and up to 60% of total biomass supply to the EU including imports. The contribution made by agricultural biomass sources from within the EU27 region is lower in Scenarios C1 and C3, at roughly around 60 Mtoe, representing 55% of biomass supplied domestically from within the EU27 region (not including black liquor), and around 45% of total biomass supply to the EU including imports.

Compared with Scenarios B and C2, the supply of forest biomass from within the EU27 region in 2030 is highest in Scenario C3 at 65 Mtoe, and is also higher for Scenario C2 at 54 Mtoe. The relative contribution made by forest bioenergy to biomass supplied domestically from within the EU27 region in 2030 is similar in Scenarios C1 and C3, at around 45%, representing, respectively, 35% and 41% of total biomass supply to the EU including imports.

The contribution made by imported forest biomass is highest in Scenarios B and C1, at 32 Mtoe, representing around 20% of total biomass supply including imports (not including black liquor). The contribution of imported forest biomass is lower in Scenarios

C2 and C3, at 19 Mtoe, representing around 12% of total biomass supply to the EU including imports (not including black liquor).

Compared with the various high-bioenergy ‘Carry on’ Scenarios discussed above, total biomass supply in 2030 (from all sources, except black liquor) is lower in Reference Scenario A, at 110 Mtoe, and lowest in Scenario D (‘Back off’), at 77 Mtoe. The main cause of the difference in these scenarios, compared with the ‘Carry on’ Scenarios, is due to reduced supply of agricultural biomass from within the EU27 region, with rather smaller overall reductions in total supply of forest biomass, which vary in terms of the relative contributions due to domestically-produced and imported sources of forest biomass.

Figure 3.12 shows a more detailed breakdown of biomass supply over time from sources within the EU27 region (not including black liquor), for the different scenarios developed in this project, showing contributions made by different types of agricultural and forest biomass feedstocks.

In most cases, all of the available potential from residues (derived from both agriculture and forestry) is used for energy supply, since the cost is lower for these biomass types, compared with biomass from crops and stemwood. The level of production of traditional firewood (18.2 Mtoe) is the same for all years and scenarios, whereas the additional amount of stemwood biomass supplied for energy differs with scenario. Scenario C3 involves the highest level of stemwood by 2050 (34.7 Mtoe), but the supply of stemwood for bioenergy is also significant for Scenarios B, C1 and C2 (23.1 to 31.6 Mtoe).

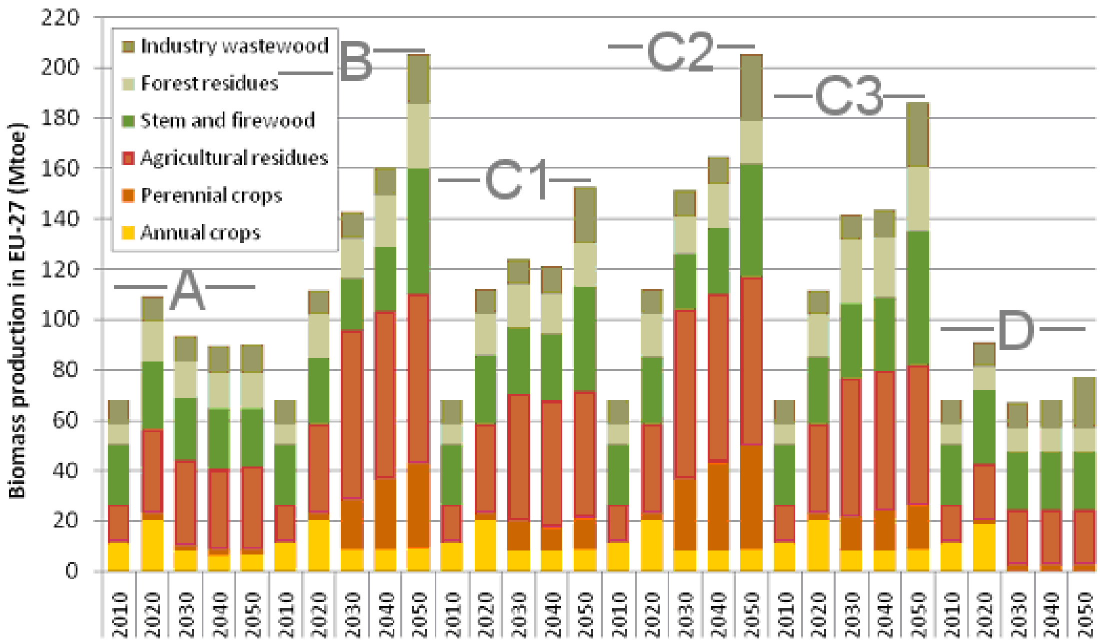

Figure 3.12. Biomass production for energy in the EU27 for the different scenarios developed in this project.

3.7.3. Biomass importation

The importation of biomass and biofuels is constrained in all scenarios. For Scenarios A, C2 and C3, the importation of solid biomass is constrained to increase by no more than 2% per year after 2020, whilst for bioliquids, the maximum level of imports remains at the 2020 level. For Scenarios B and C1, an annual increase of up to 5% per year is allowed for the importation of solid biomass and biofuels (see Table 3.2, Section 3.4). The VTT-TIAM model simulates the levels of biomass sources supplied from different geographical regions, based on biomass potentials and cost-supply data, and transport distance. However, current data on biomass potentials and costs outside Europe are very uncertain.

Currently, the southeast of the USA and British Columbia in Canada, are the two most important regions exporting wood pellets to the EU region (Lamers and Junginger, 2013). The export of wood pellets to the EU is expected to increase from about 50 PJ in 2010 to 280 PJ in 2020. About 70% of the wood pellets are projected to come from the USA and Canada. In particular, a significant contribution is expected from the southeast of the USA, based on pulp-grade plantation pine roundwood for which the demand from the pulp industry is declining (Goh *et al*., 2013). Goh *et al.* suggest that, in a speculative scenario involving very high demand for wood pellets, other regions such as countries in Latin America and Africa could become important exporting sources to the EU. The results from the VTT-TIAM model for the scenarios developed in this project also indicate the possibility of some biomass being supplied from the Latin American region, but the supply of biomass from the African and Asian regions was not indicated in the results (not least due to the application of sustainability criteria in the estimation of potentials, see Sections 3.3.3 and 3.5).

Few systematic data are available on biomass potentials outside Europe. It was assumed that, besides biofuels, only forest biomass would be imported for bioenergy, although there might also be some import of agricultural residues (e.g. straw) and pellets of perennial energy crops from Eastern European countries outside the EU region (e.g. Ukraine). However, these sources will remain relatively small.

Estimates of potentials for the supply of forest bioenergy from outside the EU region are currently based on the Global Energy Assessment (GEA, 2012), which provides biomass potentials, including for forest harvest residues, for 18 world regions. The 2050 potential for harvest residues, taking sustainability criteria into account (see Sections 3.3.3 and 3.5), is estimated at 2 EJ per year for Canada, 7 EJ per year for the United States, 3 EJ per year for the CIS region, and 3 EJ per year for Latin America. Other regions have low potentials (particularly after allowing for sustainability criteria) and are not likely to export forest biomass for bioenergy to Europe. These data have been used as part of the settings for the VTT-TIAM model in the development of scenarios in this project. As already explained, VTT-TIAM produced estimates for the levels of supply of biomass sources imported into the EU27 region from different geographical regions, under each of the scenarios developed in this project. Given the uncertainties in the results, due to the limitations in the underlying data, the results from VTT-TIAM were used as inputs to a sensitivity analysis with respect to the geographical origin of imported biomass. This analysis was carried out as part of the modelling of biogenic carbon emissions, undertaken in Task 3 of this project (see Section 4.8.3). The results of the sensitivity analysis were then applied in the later stages of the project, and are reflected in the final project results (see Section 6).

Figure 3.13 shows the simulated levels of importation of solid wood (forest bioenergy) and biofuels from outside the EU27 region for the different scenarios developed in this project. In Scenarios B and C1, by 2050, the importation of forest bioenergy and biofuels is about 3 times higher, compared with the other scenarios. For all scenarios, the levels of imported bioenergy reach the limits set as part of the inputs to the VTT-TIAM model. This means that, even in the high biomass-importation Scenario C1, the cost of imported biomass is lower compared with domestic biomass, according to the simulations made by VTT-TIAM.

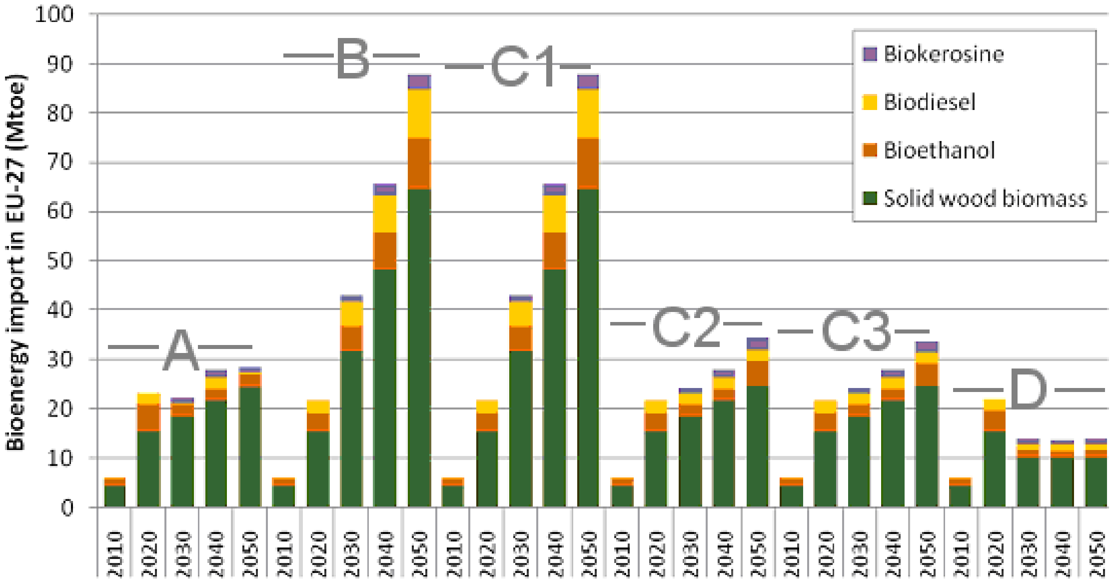

Figure 3.13. Simulated net importation of bioenergy to the EU27 for the different scenarios developed in this project.

4. Assessment of biogenic carbon emissions

4.1. Purpose

The purpose of this section is to describe the approaches taken in Task 3 of this project to the assessment of GHG emissions due to biogenic carbon of biomass consumed for energy. Scenarios for biomass consumption for energy in the EU have been developed in Task 2 and already described in Section 3 of this report. The essential results of Task 3 are estimates of the biogenic carbon emissions associated with the Task 2 scenarios for bioenergy consumption. These results are presented and discussed.

Task 3 has entailed the assembly of numerous datasets on agriculture and forests. It was necessary to appraise, analyse and fuse these datasets and, ultimately use them as inputs as part of the application of two complex models for assessing GHG emissions associated with biomass and bioenergy consumption. These steps have been critical in determining the results of this project. Consequently, a key purpose of this section is to explain how these steps were carried out and also to highlight any important assumptions made as part of the assessment.

4.2. Modelling approach

The assessment of biogenic carbon emissions has involved the use of two state-of-the-art models for simulating the vegetation and soil carbon dynamics of agricultural and forest systems. These two models are MITERRA-Europe, developed by Alterra and CARBINE, developed by Forest Research, for which brief descriptions are given in Sections 4.3 and 4.4 respectively. The intent has been to apply these models as transparently as possible, which can be challenging to demonstrate. The approach to transparency in this project has involved:

- Supporting the descriptions of the MITERRA-Europe and CARBINE models by providing examples of how particular input data and assumptions lead to the models producing certain results and outputs
- Providing descriptions of the input data to the models (notably data on areas of agricultural and forest land)
- Clearly and thoroughly stating and explaining the assumptions that have been made as part of the application of the models to represent the scenarios considered in this project.

Example calculations for the MITERRA-Europe and CARBINE models are included in Appendix 7 and Appendix 8 respectively. For CARBINE, reference is also made to examples included in the Task 1 project report and a technical report that has already described some of the outputs of CARBINE (Matthews *et al.*, 2014ab). A description of the input data to the models is given in Section 4.5 and the principles and assumptions made in developing and modelling the scenarios are discussed in Sections 4.6 to 4.8.

4.3. The MITERRA-Europe model

MITERRA-Europe, developed by Alterra, is an environmental assessment model, which calculates GHG (CO_2, CH_4 and N_2O) emissions, soil organic carbon stock changes and nitrogen emissions from agriculture on a deterministic and annual basis. MITERRA-Europe is based on the CAPRI and GAINS models, supplemented with a nitrogen leaching model, a soil carbon module and a module for representing mitigation activities (Velthof *et al.*, 2009; Lesschen *et al.*, 2011; de Wit *et al.*, 2014). The model covers 35 crops which are also represented in the Common Agricultural Policy Regionalized Impact (CAPRI) model (Britz and Witzke, 2012). In addition, five perennial energy crops (miscanthus, switchgrass, canary reed, poplar and willow) are included in MITERRA-Europe. MITERRA can represent the agriculture sector at different spatial scales, e.g. Europe can be represented at EU27 scale, Member State scale and NUTS2 scale. In addition to the biogenic carbon emissions for Task 3, the model has also been used to derive the farm-gate LCA-based GHG emissions factors for all energy crops (both annual and perennial crops) for use in calculations required as part of Task 4 (see Section 5.3).

The assessment of the biogenic carbon emissions from changes in soil organic carbon (SOC) is based on modelling the SOC balance of agricultural land areas. This involves quantifying the input of carbon to soil (manure, crop residues, and other organic inputs) and the losses of carbon from soil due to decomposition of soil organic matter. The RothC model (Coleman and Jenkinson, 1999) is applied in the calculation of the SOC balance. RothC (version 26.3) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the SOC turnover process. It uses a monthly time step to calculate total organic carbon (expressed in tC ha^{-1}), microbial biomass carbon (tC ha^{-1}) and Δ14C (from which the radiocarbon age of the soil can be calculated) on a timescale of years to centuries (Coleman and Jenkinson, 1999). For the purposes of this project, RothC has been applied to calculate the current SOC balance based on carbon inputs to soil from current agricultural practices.

In the RothC model, SOC is split into four active components and a small amount of inert organic matter (IOM) in RothC. The four active components are defined as Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each component decomposes according to a first-order process with its own characteristic rate. The IOM component is resistant to decomposition.

The RothC model requires the following input data:

- Monthly rainfall (mm)
- Monthly open pan evaporation (mm)
- Average monthly air temperature (°C)
- Clay content of the soil (as a percentage)
- An estimate of the decomposability of the incoming plant material – defined as the DPM/RPM ratio

- Soil cover (i.e. whether the soil is bare or vegetated in a particular month)
- Monthly input of plant residues (tC ha^{-1})
- Monthly input of manure (tC ha^{-1})
- Soil depth (cm)
- Initial soil carbon content, which can be provided as an input or calculated according to long term equilibrium (steady state).

For this project, climate data were derived from the WorldClim[5] database (Hijmans *et al.*, 2005) at NUTS2 level. The initial soil carbon content and clay content were derived from the LUCAS soil survey (Tóth *et al.*, 2013). LUCAS collected soil samples in 2009 at about 22,000 locations across the EU, which were analysed for a range of soil properties, including soil carbon and clay content. Average values were calculated for each NUTS2 region, separately for arable land and grassland (Figure 4.1).

Carbon input from manure was derived from MITERRA-Europe, following the allocation of manure nitrogen to crops and a CN ratio that varies with livestock type. Carbon input from crop residues was derived from the crop areas and crop yield in MITERRA-Europe and the 'harvest index', which represents the ratio between crop yield and annual net primary production (Vleeshouwers and Verhagen, 2002). For straw crops, the C input from crop residues was differentiated into straw, stubbles/chaff and below-ground C inputs from roots. Based on Scarlat *et al.* (2010), the amount of above-ground residues was calculated as a function of the crop yield. For the division between straw and other residues (stubbles and chaff) a ratio of straw to other residues of 55:45 was taken, which is based on Panoutsou and Labalette (2007) and a review by Powlson *et al.* (2011). The below-ground C input from roots and rhizodeposits, was taken to be 25% of the total assimilated C, based on Taghizadeh-Toosi *et al.* (2014). Finally, a soil depth of 23 cm was assumed, which is the default soil depth used in the RothC model.

[5] http://www.worldclim.org/

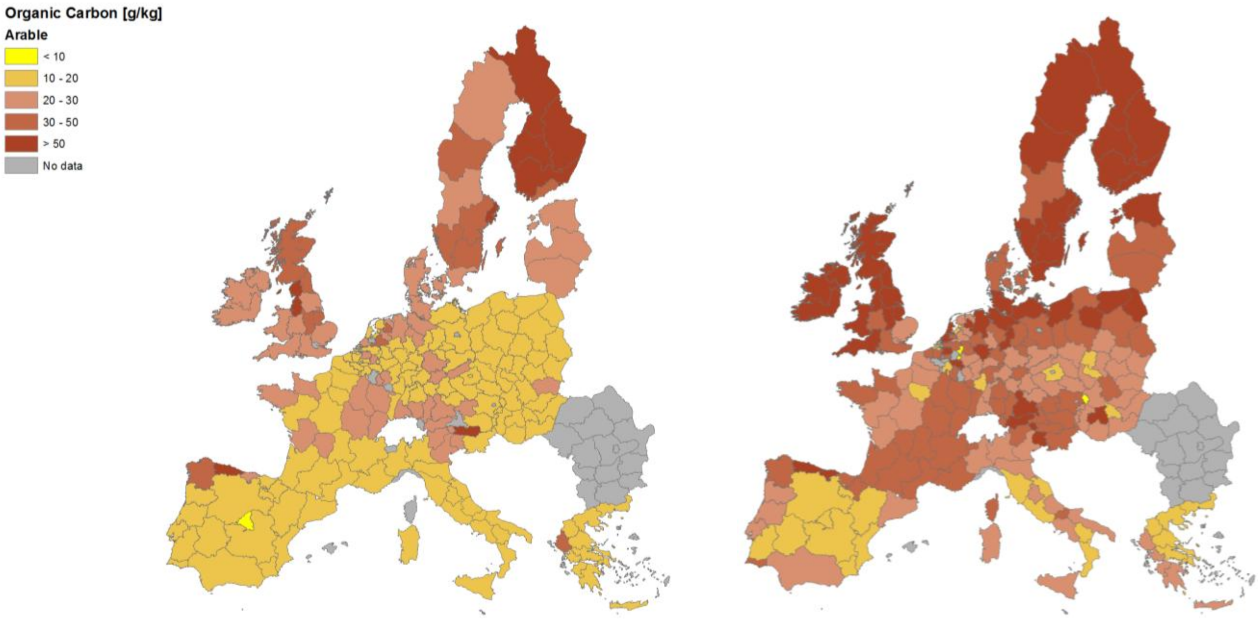

Figure 4.1. Average soil organic carbon content (gC per kg soil mass) for arable soils (left-hand figure) and grassland (right-hand figure) derived from the LUCAS 2009 soil survey.

4.3.1. Examples of calculations using MITERRA-Europe

The calculations made by the MITERRA-Europe model can be illustrated by considering simplified examples. Two example calculations are illustrated in Appendix 7, one for CO_2 emissions arising from agricultural land-use change, and one for CO_2 emissions due to increased straw removal for bioenergy. These simplified examples show how the calculation rules are applied in the MITERRA-Europe model, based on hypothetical land areas forming a notional NUTS2 region.

4.4. The CARBINE model

The CARBINE model was first developed by the Research Division of the Forestry Commission (now Forest Research) in 1988 (Thompson and Matthews, 1989). Essentially it is an analytical model of the exchanges of carbon that take place between the atmosphere, forest ecosystems (trees, deadwood, litter and soil) and the wider forestry sector (harvested wood products) as a result of tree growth, mortality and harvesting (Thompson and Matthews, 1989; Matthews, 1991; Morison *et al.*, 2012) . Other land uses are represented in CARBINE 'at the margin', i.e. to the extent necessary to represent land use transformations involving forests such as afforestation of cropland or grassland or conversion of forest to other land uses (deforestation). CARBINE also represents other economic sectors 'at the margin', notably the Energy and Construction sectors, in order to estimate the impacts of changes in patterns of timber harvesting and utilisation on consumption of fossil fuels and alternative materials, and consequent changes in GHG emissions (Matthews, 1994, 1996).

CARBINE has common features of structure and functionality with other analytical forest sector and forest carbon accounting models, notably EFISCEN (Schelhaas *et al.*, 2007), C-Flow (Dewar, 1990, 1991; Cannell and Dewar, 1995), CO_2FIX (Mohren and Klein Goldewijk, 1990; Nabuurs, 1996; Mohren *et al.*, 1999), CBM-CFS3 (Kurz *et al.*, 2009), C-change (Beets *et al.*, 1999) and GORCAM (Marland and Schlamadinger, 1995, 1999; Schlamadinger and Marland, 1996). Studies comparing CARBINE and C-Flow (the other main forest carbon accounting model developed in the UK) revealed many similarities and consistencies in the functioning and results produced by the two models (Robertson *et al.*, 2003; Matthews *et al.*, 2014c).

Simulations produced by forest sector carbon accounting models such as CARBINE have an important role in evaluating the impact on carbon stocks and sequestration of different forest management regimes involving harvesting. These models are also relevant to estimating carbon stocks in wood products for different geographical regions, and ultimately impacts due to the utilisation of wood fuel and wood products in place of fossil fuels and non-wood materials. Forest carbon accounting models have been used extensively to address key questions about forest policy and management options and their impact on carbon stocks and carbon sequestration in both forests and wood products, such as:

- What is the impact on carbon stocks and sequestration of establishing a new forest stand managed for wood production?
- What would be the impact on carbon stocks and sequestration of introducing a programme of regular harvesting in a forest area that previously was not subject to significant human intervention?
- What would be the impact on GHG emissions of changing the uses of harvested wood, for example, diverting the use of wood from use in timber products to use for bioenergy?

Initial versions of CARBINE produced per-hectare scale estimates of carbon exchanges associated with individual stands of trees (Thompson and Matthews, 1989; Matthews, 1994). Subsequently CARBINE was further developed into a national-scale scenario analysis tool and has been used to assess the impacts of current and alternative forestry practices on greenhouse gas balances in Great Britain and the United Kingdom (Matthews, 1991, 1996; Matthews and Broadmeadow, 2009). Recently CARBINE has been further developed for application to National GHG Inventory calculations for the UK LULUCF sector, taking over from the C-Flow model in 2013. The application of CARBINE has permitted a more complete and refined representation of Forest Land within the UK's LULUCF GHG Inventory. CARBINE has also been applied in an international context to provide forestry projections for many countries in support of discussions amongst parties to the UNFCCC. The CARBINE model also has the capacity to produce estimates of other variables not directly to do with forest carbon but of great relevance to decisions about forest management, for example:

- Levels of wood and timber production (which can be broken down into specific wood product categories if required)
- The development of forest age class distribution over time
- Changes in the species composition of forests in response to management interventions (where relevant).

Most recently CARBINE has been extended to represent the impacts of different types of natural disturbance events.

In terms of documentation, the CARBINE model has been described and discussed in a number of papers (Thompson and Matthews, 1989; Matthews, 1991, 1994, 1996; Matthews and Broadmeadow, 2009; Morison *et al.*, 2012). The development and improvement of the model has been a significant exercise covering many years and the publication of a complete description of CARBINE is planned.

A schematic diagram of the structure of the CARBINE model is given in Figure 4.2.

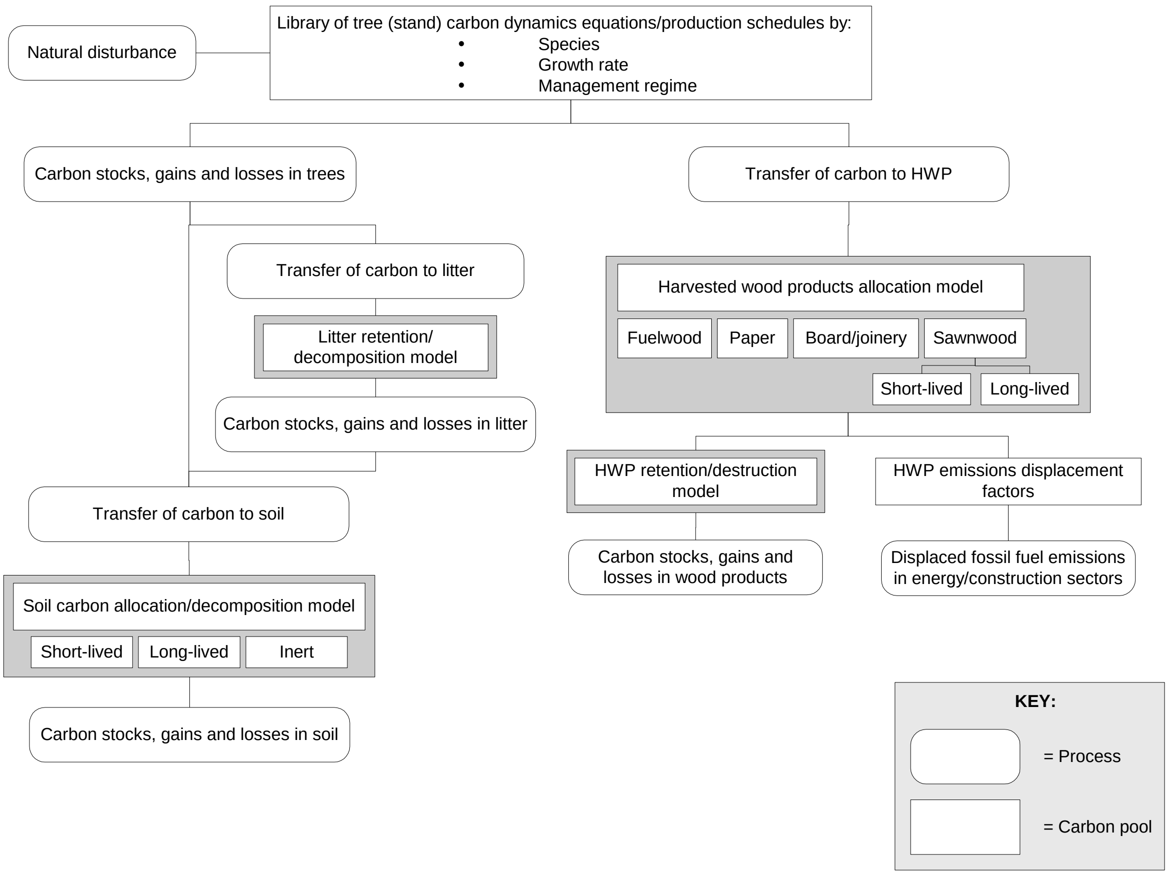

Figure 4.2. Diagram illustrating the scope, structure and function of the CARBINE model.

4.4.1. Tree growth, management and wood production

The main driving module of CARBINE consists of a set of computerised mathematical functions and algorithms describing the accumulation (and loss) of carbon in tree biomass of different forestry systems at the per-hectare scale. Different functions and algorithms are used to represent distinct forestry systems, defined in terms of:

- Tree species composition
- Tree growth rate (yield class)
- Management regime applied.

The tree species and growth rates represented are based on yield models originally produced by the British Forestry Commission (Edwards and Christie, 1981). Although these were developed for application in the UK, a review of yield models in Europe and other countries has strongly suggested that the Forestry Commission yield models are robust as a fundamental basis for simulating potential wood production and carbon dynamics of forest species in many temperate, boreal and Mediterranean countries (Christie and Lines, 1979). The tree species covered include examples for coniferous species of spruces, pines, firs, larches, cedars, cypresses and all the major temperate and boreal broadleaf tree species. Growth rates in terms of mean annual increment of stem volume can be represented in the range from 2 m^3 ha^{-1} yr^{-1} up to 30 m^3 ha^{-1} yr^{-1}, with extrapolation possible to growth rates up to 50 m^3 ha^{-1} yr^{-1}, enabling tropical growth conditions to be represented.

As already explained, the mathematical functions describing forest development and levels of harvesting are based on standard models of forest growth and yield developed by the British Forestry Commission (Edwards and Christie, 1981). However, these are implemented in CARBINE as a dynamic yield model, known as M1 (Arcangeli and Matthews, unpublished model), which enables the representation of a wide range of management prescriptions (e.g. in terms of patterns of thinning and felling). Basic management regimes represented in the CARBINE model include:

- No thinning and no felling (i.e. effectively no management for production)
- No thinning with clearfelling on a specified rotation
- Thinning with clearfelling on a specified rotation
- ‘Continuous cover’ silviculture (i.e. forest management with harvesting that also aims to always maintain tree cover on the land).

It is also possible to specify detailed rotations and levels of thinning, and changes in the management of forest areas over time, involving transitions between the broad management regimes indicated above, and also adjustments to rotations and transitions in tree species and growth rates on restocking.

4.4.2. Tree biomass and carbon

In CARBINE, stem biomass is estimated by multiplying estimates of stem volume by a value for the basic density of wood for the relevant tree species, expressed as oven dry tonnes of mass per cubic metre of 'green' timber volume (Lavers, 1983). Biomass estimates are converted to equivalent estimates of carbon by multiplying by a standard value for wood carbon content of 0.5 tC odt^{-1} (Matthews, 1993).

Carbon and biomass in tree roots, branches and foliage are estimated based on allometric relationships with stemwood (Matthews *et al.*, 2014c). These relationships are based on interpretation of summary estimates of root, branch, foliage and stem biomass using the Forestry Commission BSORT forest stand biomass model (Matthews and Duckworth, 2005; Jenkins *et al.*, 2014).

4.4.3. Deadwood and litter carbon

CARBINE includes a sub-model for representing accumulation and loss of carbon in dead wood and litter. Inputs of litter are related to the standing biomass of trees and also to rates of tree mortality. Levels of tree mortality are represented implicitly in the standard Forestry Commission growth models, and explicit estimates are included in models for stands subject to no thinning, where mortality levels are high. Root and branch wood volume associated with dead trees is estimated in the same way as for living stemwood, by reference to allometric relationships. Deadwood and litter is assumed to decay according to a first order process, with rate constants that are normally set to be consistent with boreal and temperate conditions (Repo *et al.*, 2011, 2012) but can be adjusted for Mediterranean and tropical conditions.

4.4.4. Soil carbon

The CARBINE model includes three optional sub-models for representing the accumulation and loss of soil organic matter:

- Version 1, based on IPCC Tier 1 emissions factors for forest soils
- Version 2, a very simplified representation of soil carbon dynamics involving three soil carbon components (inert, slow turnover, fast turnover) calibrated for UK soils
- Version 3, a representation of soil carbon dynamics based on an early version of the RothC model (Jenkinson and Rayner, 1977), extended to represent the carbon dynamics and GHG emissions of organic soils (IPCC, 2014; Yamulki *et al.*, 2013; Hargreaves *et al.*, 2003).

Version 3, which has been applied for the purpose of this project, is very similar to well-established soil carbon models such as RothC (Coleman and Jenkinson, 1999) and ECOSSE (Smith *et al.*, 2007), as already described for the MITERRA-Europe model in Section 4.3. In CARBINE, inputs of organic matter to forest soils are assumed to be primarily due to fine root turnover, which is assumed to be asymptotically related to tree carbon stocks. A secondary contribution to soil carbon inputs is made by the transfer of carbon from litter. The relative contributions due to fine root turnover and litter vary with soil type and tree species/growth rate. The annual input of organic matter is calibrated to produce changes in (and levels of) soil carbon stocks typically observed for transitions between forest and non-forest vegetation cover (IPCC, 2006; Bradley *et al.*, 2005), allowing for variations in soil properties.

4.4.5. Wood products

Of particular importance for this project, the CARBINE model includes a very sophisticated representation of the fate of forest biomass and carbon following harvesting and conversion into useful wood products, including bioenergy. The general approach is illustrated by Figure 3.3, which shows the detailed allocation of harvested wood to litter in the forest and to a range of different primary wood products.

The first step involves an initial allocation to waste wood left as litter in the forest and to three 'raw' stemwood categories of 'bark', 'small roundwood' and 'sawlogs'. The proportion of stemwood allocated to litter is determined by an allocation coefficient, which is set to a standard value of 10% (see for example Forestry Commission, 2014). The allocation of the remaining stem material to bark, small roundwood and sawlogs (otherwise known as a product assortment) is also determined by allocation coefficients which depend on the size and shape of the harvested trees. In turn, tree size and shape depend on many factors but notably tree species, growth rate and how the trees have been managed (Matthews and Mackie, 2006). The specific definitions used for small roundwood and sawlogs also influence these allocations.

In the CARBINE model, coniferous (softwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stemwood (as opposed to taking a specified fixed length), up to a minimum top diameter of 18 cm over bark, but with a minimum length constraint of 1.3 m, excluding that portion of stemwood allocated to litter. Broadleaf (hardwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stemwood (as opposed to taking a specified fixed length), up to a minimum top diameter of 24 cm over bark, but with a minimum length constraint of 1.3 m, excluding that portion of stemwood allocated to litter. The more conservative specification of sawlogs adopted for broadleaves compared to conifers reflects differences in the utilisation of the two broad types of timber, but also allows for the occurrence of significant branching and forking of tree stems in broadleaves (generally higher up the stem and at smaller top diameters), which limit the suitability of such material for utilisation as sawlogs.

Small roundwood is defined as the remaining portion of stem material (excluding any portion allocated to litter) to a minimum top diameter of 7 cm over bark. By convention in the forest industry, sawlog volume (or biomass or carbon) is expressed as an under-bark quantity, whilst small roundwood is expressed as an over-bark quantity (i.e. including any associated bark). In CARBINE, quantities of harvested sawlogs and small roundwood are both calculated on an under-bark basis because this approach is more appropriate for the methodology used in the model for allocation of harvested carbon to raw and ultimately primary wood products. The calculation of the bark, small roundwood and sawlog allocation coefficients is based on tables given in Matthews and Mackie (2006) and Edwards and Christie (1981).

A further set of allocation coefficients are used to determine how branchwood, small roundwood, sawlogs and bark are used for different primary products, as shown in Figure 3.3. These allocation coefficients can be specified for different tree species. It is also possible to specify changes and trends in the allocation coefficients over time, for example to represent the progressive diversion of harvested wood from use for one type of product to another. A further refinement permits the setting of a threshold with respect to the mean size of harvested trees, which affects whether the trees are harvested as whole stems for use as bioenergy or converted to sawlogs and small roundwood and allocated to a range of primary products. Specifically, if the percentage of sawlog volume in stemwood of harvested trees falls below the threshold, then all stemwood and 90% of branchwood are allocated to use for bioenergy. If the percentage is above the threshold, then allocation to wood products follows the scheme in Figure 4.3. The setting of the threshold can be varied by tree species and over time, allowing this treatment of harvested trees to be represented dynamically. This facility has been included in CARBINE to allow the detailed representation of patterns in the use of harvested wood over the life cycle of a stand of trees (see Section 2.3 of the Task 1 project report, Matthews *et al.*, 2014a). It also permits the representation of possible trends in the use of harvested wood, notably recent interest in the use of early thinnings primarily to supply bioenergy.

The CARBINE model also includes a sub-model to represent the retention of carbon in harvested wood products and the eventual release of carbon to the atmosphere when wood products are destroyed or decay. However, this sub-model has not been applied for the purposes of this project. Instead, the retention and loss of carbon associated with harvested wood products has been represented in the workbooks of integrated results (see Sections 5.7 and 6.2 of this report).

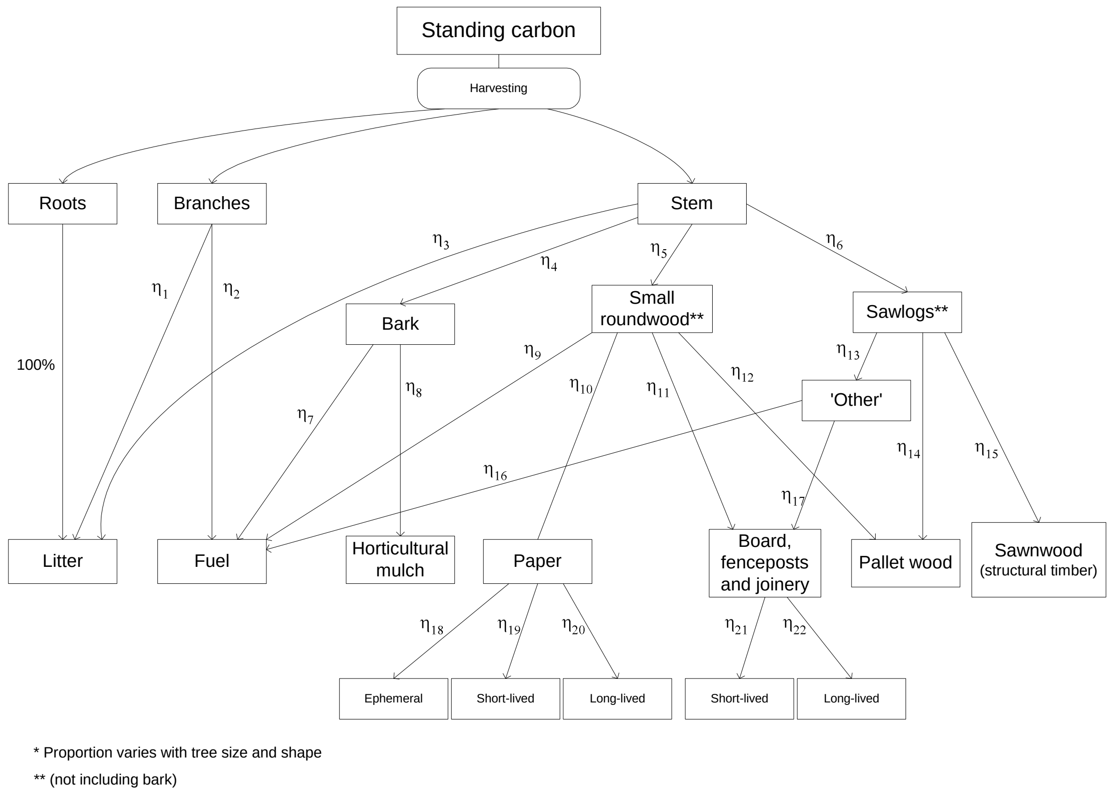

Figure 4.3. Schematic illustration of allocation of harvested wood material to primary wood products and litter as implemented in the standard version of CARBINE.

4.4.6. Input data to CARBINE

To run the CARBINE model, it is necessary to provide input data on forest areas broken into components consisting of:

- Area of forest component (ha)
- Year in which the forest component was originally planted or naturally regenerated
- Soil type associated with the forest component (essentially mineral or organic)
- Land use prior to planting or regeneration of forest (essentially arable or grassland)
- Species composition of forest component (including details of any changes in species over time)
- Potential productivity of forest component (expressed as maximum potential stem volume production, in even-numbered classes of cubic metres per hectare per year, see Appendix 2 of the Task 1 report of this project, Matthews *et al.*, 2014a); potential productivity may also be specified to change over time
- Management prescription (details of any thinning, felling and rotation to be applied, including specifying how these details may change over time)
- Specification for how any harvested wood is used (vectors of allocation coefficients and thresholds, see earlier description).

4.4.7. Examples of calculations using CARBINE

The calculations made by the CARBINE model can be illustrated by considering simplified examples, such as provided in Appendix 8. It should be noted that examples of CARBINE simulations have been presented in several previous reports. It is suggested that reference is made to the examples already reported in Section 3 of Matthews *et al.* (2014b)[6] and Section 3 of the Task 1 report for this project (Matthews *et al.*, 2014a). These examples focus on results of CARBINE for forest carbon stocks and stock changes. The example presented in Appendix 8 illustrates results for carbon stocks and also for other outputs of CARBINE of relevance to this project. This example also represents one of the ways in which CARBINE can be applied to assess the impacts of forest management interventions to increase the supply of forest bioenergy.

4.5. Data Sources

4.5.1. Agricultural data sources

The types of input data required for the MITERRA-Europe and RothC models have already been described in Section 4.3. Table 4.1 summarises the data sources that were referred to in order to develop simulations with MITERRA-Europe and RothC.

Table 4.1 Summary of data sources referred to as inputs to the MITERRA-Europe and RothC models

Input data	Source
Monthly rainfall (mm)	Derived from the WorldClim[7] database (Hijmans *et al*., 2005) at NUTS2 level.
Monthly open pan evaporation (mm)	
Average monthly air temperature (°C)	
Clay content of the soil (as a percentage)	Derived from the LUCAS soil survey (Toth *et al*., 2013), separately for arable land and grassland.
An estimate of the decomposability of the incoming plant material – defined as the DPM/RPM ratio	Based on Coleman and Jenkinson (1999)
Soil cover (i.e. whether the soil is bare or vegetated in a particular month)	Derived from the crop areas in MITERRA-Europe.

[6] Note that examples of results for CARBINE reported in Matthews *et al*. (2013) have been produced using version 2 of the soil carbon sub-model of CARBINE. Version 3 has been used in this project, which produces quite different results, generally more conservative in terms of potential for soil carbon sequestration.
[7] http://www.worldclim.org/

Table 4.1 (continued) Summary of data sources referred to as inputs to the MITERRA-Europe and RothC models

Input data	Source
Monthly input of plant residues (tC ha^{-1})	Derived from the crop areas and crop yield in MITERRA-Europe and the 'harvest index', based on available literature (Vleeshouwers and Verhagen, 2002; Panoutsou and Labalette, 2007; Powlson *et al.*,2011; Taghizadeh-Toosi *et al.*, 2014)
Monthly input of manure (tC ha^{-1})	Derived from outputs of the MITERRA-Europe model, following the allocation of manure nitrogen to crops and a CN ratio that varies with livestock type.
Soil depth (cm)	23 cm was assumed, which is the default soil depth used in the RothC model.
Initial soil carbon content	Derived from the LUCAS soil survey (Toth *et al.*, 2013), separately for arable land and grassland.

4.5.2. Forestry data sources

The types of input data required for the CARBINE model have already been described in Section 4.4. Table 4.2 summarises the data sources that were referred to in order to develop simulations with CARBINE. Note that, for the modelling of forest bioenergy sources relevant to this project, this involved obtaining data on forests for significant areas outside the EU27 region, specifically for Canada, USA, the countries representing CIS, and to lesser extent potential sources of forest bioenergy in Latin America.

It must be stressed that systematic and comprehensive data on forests are not readily available for all regions, notably for the EU27 region. For this project, it was necessary to compile the best available data sources, make expert interpretations of the data, and fuse them to provide consistent datasets that could be used. Appendix 9 gives details of the assessments made of available data sources, and of the approach taken in preparing input datasets for the CARBINE model.

Table 4.2 Summary of data sources referred to as inputs to the CARBINE model

Input data	Source
Area of forest component(s)	Depends on region. For the EU27 region and for countries representing CIS, several available data sources were referred to notably an on-line database maintained by UN-ECE (http://w3.unece.org/pxweb/), and the EFISCEN on-line database (http://www.efi.int/portal/virtual_library/databases/efiscen/inventory_database/). EU27 data was supplemented by a number of supporting sources of information, notably a published review of European forests and forestry (Arkuszewska *et al.*, 2006). For Canada and the USA, National Forest Inventories are reported on-line (https://nfi.nfis.org/reporting.php?lang=en and http://apps.fs.fed.us/Evalidator/evalidator.jsp respectively). For Latin America, the most relevant forest types were considered to be high-productivity tree plantations established on degraded former agricultural land (see ABRAF, 2011, www.youblisher.com/p/200491-ABRAF-Statistical-yearbook-2011; Couto *et al.*, 2011, http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_PR2011-02.pdf).
Year in which the forest component was originally planted or naturally regenerated	
Soil type associated with the forest component	Forest areas from Global Land Cover 2000, http://bioval.jrc.ec.europa.eu/products/glc2000/products.php; soils data from Harmonized World Soil Database, http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/.
Land use prior to planting or regeneration of forest	For this project, this information is only relevant for recent afforestation activities. An assumption was made that all afforestation takes place on marginal land or grassland, rather than former arable land. This assumption leads to conservative estimates of potential sequestration of carbon in soils following afforestation.
Species composition of forest component	See area of forest component(s)

Table 4.2 (continued) Summary of data sources referred to as inputs to the CARBINE model

Input data	Source
Potential productivity of forest component	Based on interpretation and fusion of available data sources including the EFISCEN database, Christie and Lines (1979), the Canadian and USA National Forest Inventories, ABRAF (2011) and Couto *et al.* (2011).
Management prescription	Based on interpretation and fusion of available data sources. Expert judgement and modelling were also required (see Section 4.8).
Specification for how any harvested wood is used	Forestry Commission (2014); UNECE and FAO (2012)
Statistics on existing levels of wood production	Data on levels of industrial roundwood and woodfuel production by countries for the years 1990, 2000 and 2005, have been reported in Table 13 of the Global Forest Resource Assessment 2010 (FRA) compiled by the FAO www.fao.org/forestry/fra/fra2010/en/

Systematic information on growth rates of forest areas in the EU27 region, for Eastern Europe and for Canada are not available. It was necessary to refer to the best available data source and to fill gaps through expert interpretation of available literature. For many regions and forest types, the analytical review of Christie and Lines (1979) was used as a guide to the assignment of growth rates to forest areas. The main results available in the paper of Christie and Lines, on growth rates for Norway spruce, Sitka spruce, Scots pine and lodgepole pine, are summarised in Figures 4.4 and 4.5.

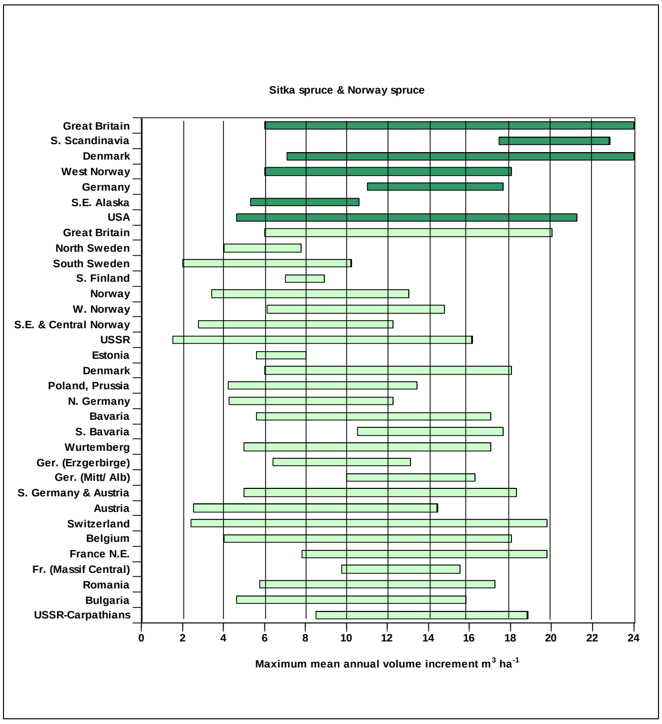

Figure 4.4. Growth rates of Norway spruce (light green) and Sitka spruce (dark green) observed in a range of countries and regions (after Christie and Lines, 1979).

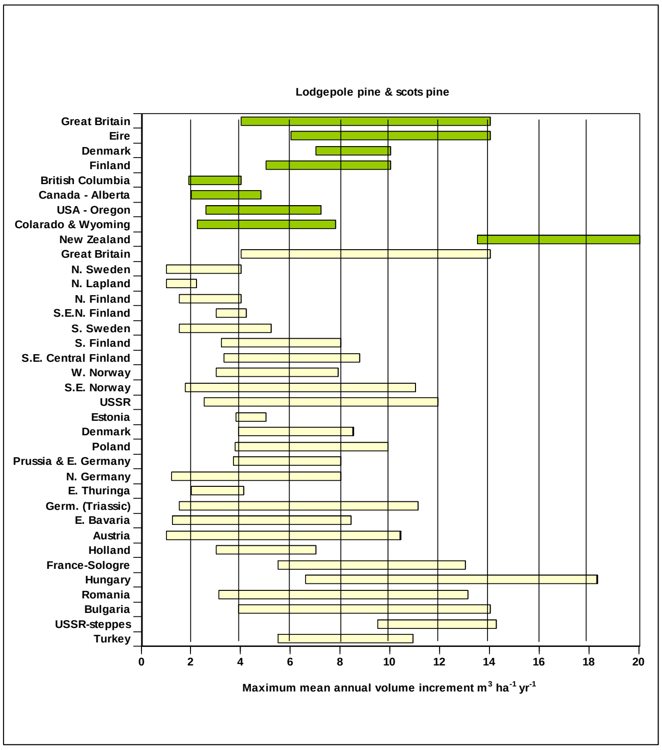

Figure 4.5. Growth rates of Scots pine (cream) and lodgepole pine (green) observed in a range of countries and regions (after Christie and Lines, 1979).

Information on the management of forest areas is extremely difficult to find. For the purposes of this project, it was necessary to model the management of forest areas in different countries and regions, by inferring rotations and areas under management for production from available statistics on levels of wood production. The approach to this is discussed in Section 4.8.1. An important aspect of the modelling of forest management under baseline conditions involved assigning rotations to forest areas, where these are under management for production. These rotations should be typical of current forestry practice in forest areas of given species, growth rate and regional circumstances. These rotations are referred to in this report as 'characteristic rotations'. Details of the assumptions about characteristic rotations for different forest types in different regions are summarised in the tables in Appendix 9.

4.6. Key assumptions and approaches

The modelling approach has referred to a number of key principles and assumptions, many of which flow from the literature review undertaken for Task 1 of this project (see Matthews *et al.*, 2014a and Section 2 of this final project report).

As a fundamental principle, the particular approach to LCA known as consequential LCA has been adopted for the calculation of GHG emissions associated with scenarios for increased biomass consumption for energy in the EU. The rationale for this choice of methodology is discussed thoroughly in Section 4 of the Task 1 project report (Matthews *et al.*, 2014a). It follows that it has been necessary for the application of models in Task 3, and any subsequent processing and interpretation of results, to be consistent with the methods of consequential LCA. In particular, the GHG emissions associated with biogenic carbon of biomass need to be estimated by modelling 'how the world will look' under a specified scenario for increased bioenergy consumption, compared with 'how the world would have looked' under a scenario in which the increased bioenergy consumption does not occur (i.e. the counterfactual scenario). Such a comparative assessment requires model simulations to be developed for the counterfactual scenario as well as the scenario for increased bioenergy consumption, and both the counterfactual and scenarios require careful definition and specification.

The application of the principles and methods of consequential LCA, to meet the objectives of this project, has been described earlier in this report (Section 3.3.1), where the approach to the development of scenarios in Task 2 was discussed. As already highlighted in that discussion, the five scenarios developed in this project represent options for decisions that may be taken to enhance or reduce future contributions made by biomass sources to the supply of energy in the EU. In addition, the scenarios permit an assessment of the sensitivity of impacts to the approaches taken to the use of biomass. The assessment undertaken in Task 3 has involved the investigation of the dependence of outcomes, in terms of biogenic carbon emissions, on the approaches taken to producing the levels of biomass specified by the scenarios developed in Task 2. This is particularly important in the case of forest bioenergy, for which biogenic carbon emissions can vary considerably, depending on the approaches taken to forest management and wood use. Hence, the assessment in Task 3 has involved developing storylines for agricultural land use and forest management involved in the production of biomass for use as energy, Key assumptions adopted as part of this assessment are considered below.

When considering agricultural biomass, the main cause of biogenic carbon emissions is land-use change involved in the increased supply of biomass for energy. Biogenic carbon emissions can also occur as a result of changes to land management practices e.g. increased use of the residual biomass of food crops such as straw.

The counterfactual scenario for agricultural land use and management can be defined as 'business as usual'. For the purposes of this project, business as usual has been assumed to involve the continuation of current agricultural land uses and practices in the EU, in the absence of increased demand for biomass for energy. No assumptions have been made about future developments in the use and management of agricultural land in response to trends in demand for food or other agricultural products. The development of scenarios has involved specifying how agricultural land use and management in the EU will change to achieve increases in the supply of bioenergy over time, as required for each of the scenarios developed in Task 2 of this project. Having established the details of agricultural land use and management for the counterfactual scenario, and any changes involved for a given scenario, the MITERRA-Europe model has been used to simulate the development of agricultural biomass and soil carbon stocks for both scenarios. The GHG emissions associated with biogenic carbon arising from changes in agriculture to supply increased bioenergy have then been estimated as the difference between the results for a scenario and the counterfactual scenario. It should be noted that the approach to estimating non-biogenic GHG emissions associated with agricultural biomass production and processing is different. This subject is covered in the description of work on Task 4 of this project (see Section 5).

Indirect land-use change (iLUC) is a contentious but important potential cause of biogenic carbon emissions associated with changes to agricultural land use and management to increase supplies of bioenergy. The possibilities for the occurrence of iLUC, and its potential impacts, had to be addressed in developing and modelling the biomass and counterfactual scenarios considered in this project. A precautionary principle has been adopted, which has involved constraining the extent of changes in agricultural land use and management represented in the biomass scenarios, to ensure that significant risks of iLUC should not arise.

In the case of forest bioenergy, biogenic carbon emissions can also occur as a result of land-use change in response to increased demand for bioenergy. Both positive and negative land-use changes involving forest land are possible, i.e. afforestation to increase the extent of the forest resource, and unsustainable harvesting of forest areas leading to permanent deforestation. However, opportunities for afforestation may be quite limited without incurring serious risks of iLUC, whilst the EU regulates against deforestation internally and also against the importation of wood from unsustainable sources. It is more likely that the main actions to increase the supply of forest bioenergy will involve changes to the management of existing forest areas (i.e. increased harvesting of trees or extraction of harvest residues from forests), or the diversion of the use of harvested wood from use for the manufacture of material products. Section 2 of the Task 1 report for this project has discussed the diversity of ways in which forest management and patterns of wood use might change to meet increased demand for wood for bioenergy.

As with agriculture, the counterfactual scenario for forest management and wood use can be defined as 'business as usual'. For the purposes of this project, business-as-usual forest management has been assumed to involve the continuation of the management currently prescribed for forest areas in the EU, and also in countries importing wood to the EU, in the absence of increased demand for biomass for energy. This has required the modelling of thinning and felling in forest areas using the CARBINE model, including assumptions about rotations applied to forest stands, to meet existing levels of wood supply. No assumptions have been made about future developments in the management of forest areas in response to trends in demand for either bioenergy or material wood products. This point is important: the alternative would have been to define a business-as-usual scenario that allowed for any existing trends in demand for wood including forest bioenergy. This would have resulted in biogenic carbon emissions due to any existing trends in the supply of forest bioenergy being included as part of the modelling of the counterfactual scenario. Because the assessment of GHG emissions for a given scenario involves comparison with the counterfactual scenario, this would have had the effect that these GHG emissions would not be included in estimates for the scenario. The approach taken in this project has thus been precautionary, in that biogenic carbon emissions due to any changes from current forest management practices to increase bioenergy supply are included in estimates for the scenarios.

A similar approach has been adopted in defining a business-as-usual pattern of wood use. Specifically, harvested wood has been assumed to be used to supply existing levels of bioenergy and material wood products, with no allowance for any existing trends, e.g. increased demand for forest bioenergy or (potentially) reduced demand for paper or wood based panels. Again, the approach has been precautionary, in that any changes in GHG emissions due to reduced consumption of wood material products (compared with existing levels) and the increased use of wood for bioenergy (as an alternative market) are included in estimates for the scenarios.

The development of scenarios for agriculture has involved specifying how agricultural land use and management in the EU will change to achieve increases in the supply of bioenergy over time, as required for each of the scenarios developed in Task 2 of this project. Having established the details of agricultural land use and management for the counterfactual scenario, and any changes involved for a given scenario, the MITERRA-Europe model has been used to simulate the development of agricultural biomass and soil carbon stocks for both scenarios. The GHG emissions associated with biogenic carbon arising from changes in agriculture to supply increased bioenergy have then been estimated as the difference between the results for a scenario and the counterfactual scenario.

The development of scenarios for forestry has also involved specifying how land use may change (through afforestation and deforestation) to achieve increases in supply of bioenergy over time. Having established the details of afforestation and deforestation for the counterfactual scenario, and any changes involved for a given scenario, the CARBINE model has been used to simulate the development of forest biomass and soil carbon stocks for both scenarios. The GHG emissions and/or carbon sequestration due to afforestation or deforestation associated with increased bioenergy supply have then been estimated as the difference between the results for a scenario and the counterfactual scenario. However, the principal task in the development of scenarios for forestry has required specifying how the management of existing forest areas may change to achieve increase in supply of bioenergy over time. Having established the details of forest management for the counterfactual scenario, and the scenario, the CARBINE model has again been used to simulate the development of forest biomass and soil carbon stocks for both scenarios. The GHG emissions and/or carbon sequestration due to changes in forest management involved in increased bioenergy supply have then been estimated as the difference between the results for a scenario and the counterfactual scenario.

The development of scenarios for agricultural land use and management is discussed further in Section 4.7.1. The development of scenarios for afforestation and deforestation is discussed in Sections 4.7.2 and 4.7.3 respectively. The development of scenarios for forest management is discussed in Section 4.8.

It should be noted that the approach to estimating non-biogenic GHG emissions associated with agricultural and forest biomass production and processing is different. This subject is covered in the description of work on Task 4 of this project (see Section 5).

4.6.1. Countries included in modelling of agriculture and forestry

As explained in Sections 1.4 and 3.3.2, for the purposes of this project, it was assumed that all biomass of agricultural origin consumed for heat and/or power generation in the EU region would also be produced in the EU region. However, the different scenarios developed in Task 2 explicitly recognised that forest biomass could be produced within the EU region and also imported from other countries. It was, therefore, necessary to represent the potential contributions due to forestry in a wide range of relevant regions and countries, as already identified in Task 2. Table 4.3, which is an abbreviated version of Table 1.1 in Section 1.4, shows how the countries of key regions potentially supplying the EU with forest bioenergy have been represented.

Table 4.3 Representation of countries in regions supplying forest bioenergy to the EU

Region	Representation
EU27	Forests, forest management and wood production in each EU27 Member State were modelled individually. Cyprus and Malta were excluded due to their small forest areas.
CIS	Forests, forest management and wood production were modelled individually for Belarus, European Russia (effectively west of the Urals) and Ukraine
Canada	Forests, forest management and wood production were modelled individually for six ecological zones represented in the Canadian National Forest Inventory
USA	Forests, forest management and wood production were modelled individually for each of the conterminous States of the USA
LAM	Forest bioenergy supplied from the LAM region was assumed to be restricted to production from purpose-grown plantation forests established on abandoned and degraded agricultural land in Brazil. Contributions from Brazil to forest bioenergy supply were not included in all scenarios (see Sections 4.7.2 and 4.8).

4.7. Scenarios for land use

4.7.1. Agricultural land use

To assess the biogenic carbon emissions related to agricultural land use change, a baseline of land use (change) was needed. For this we used the CAPRI baseline scenario for the years 2010, 2020, 2030, 2040 and 2050. CAPRI (Common Agricultural Policy Regionalized Impact) is an agricultural sector model at a NUTS2 level in EU27, with a global market model for agricultural products (Britz and Witzke, 2012). It combines about 400 supply models for NUTS2 regions with a global market model for a range of primary and processed agricultural products. CAPRI is the only available model which predicts EU markets and production responses at the regional level for the whole EU.

The CAPRI data provide a plausible overview, taking account of the specific diverse regional circumstances in the EU, of what land use changes can be expected by 2020 and further and the extent to which they can be related to dedicated bioenergy cropping. For the assessment in this study, land use (i.e. crop areas) is based on the most recent CAPRI baseline run 2008-2050, providing intermediate results for 2010, 2020, 2030 and 2050. This baseline run can be seen as the most probable future; simulating the European agricultural sector under status-quo policy and including all future changes in policy already foreseen in the current legislation. It also assumes all policy regarding bioenergy targets as agreed up to the present and further specified in the Trends to 2050 report (European Commission, 2013).

CAPRI also accounts for the demand for first generation biofuels (bioethanol and biodiesel), which was derived from the PRIMES model. The biofuel demand, coming from annual arable crops (e.g. oil seed rape, sunflower, wheat, barley, maize, sugar beet), is added to the total market demand for these crops. The CAPRI module then determines the match between the total biomass demand and the best mix of biomass crops and distribution over production countries, according to several production and market constraints internal to the CAPRI model. For this study it was assumed that the projected biomass use of annual crops for biofuel is derived from the CAPRI baseline crop production and that these crop areas do not change among scenarios.

CAPRI does not provide crop areas for perennial energy crops, but it does have an aggregate category of new energy crops. For more specific data on perennial energy crops (miscanthus, switchgrass, canary reed, willow and poplar), reference was made to the potential crop areas and crop yields from the bioenergy potential study of EEA (2013). Land availability for perennial energy crops was based on the amount of land released, fallow and abandoned land per NUTS2 region, see Elbersen *et al.* (2013) for further details.

Figure 4.6 shows the potential area of dedicated energy crops per country as projected by CAPRI. The total potential area for new energy crops in the EU27 increases from 12.9 million ha in 2020 to 15.1 million ha in 2030 and later decreases to 11.3 million ha by 2050. The potential land area available for afforestation was also estimated, which was used in the Task 3 work for forestry (see Section 4.7.2). Based on the potential area of dedicated energy crops from CAPRI and the actual area of energy crops projected in the scenarios, it was assumed that the remaining part of this potential area could be used for afforestation.

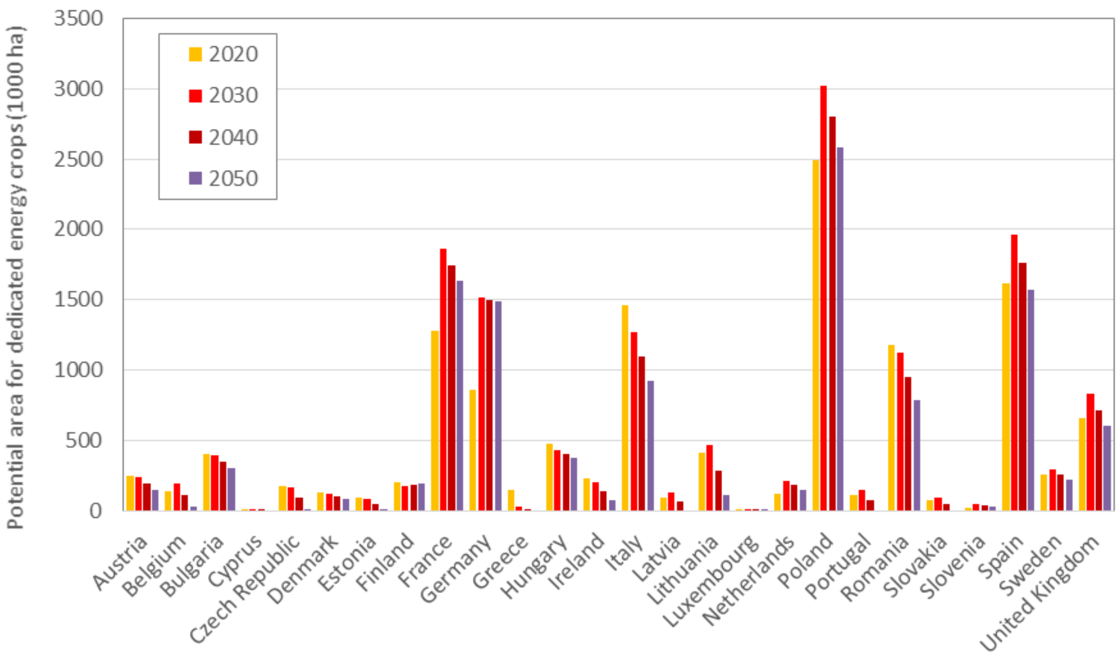

Figure 4.6. Potential crop area for dedicated energy crops (i.e. perennial energy crops) as projected by CAPRI.

4.7.2. Afforestation

For the construction of baseline simulations using the CARBINE model, assumptions needed to be made about future rates of afforestation in the EU27 region and other regions that may be involved in supplying forest bioenergy to the EU27 region.

The main source of information referred to for these afforestation rates was the JRC LULUCF spreadsheet tool. This was developed to assess the potential contribution of GHG emissions and removals in the Land Use, Land-Use Change and Forestry (LULUCF) Sector to meeting international targets for GHG emissions reduction (Grassi, 2011). The JRC LULUCF tool provided annual estimates of afforestation between the years 1990 and 2008 for all EU27 Member States. This information was supplemented with data for other countries from UNFCCC national reports, from the research literature and, where necessary, through communications with national experts (W.A. Kurz, personal communications).

There have been significant afforestation activities in the period 1950 to 1990 in many of the countries relevant to this study. In part this was in response to expanding demand for wood products but a significant aspect of afforestation in this period was concerned with reversing earlier deforestation and forest degradation due to over-exploitation of forests in the early twentieth century, partly as a result of major wars, and also as a result of industrialisation in earlier centuries. More recently, rates of afforestation have declined significantly. There are a number of reasons for this decline, including availability and cost of land, competing land uses, and a general reduction in incentives and national programmes supporting afforestation. For baseline/counterfactual simulations, it was assumed that the rate of afforestation estimated for the year 2008 would gradually decrease to zero in the year 2030, with no afforestation taking place thereafter. The patterns of historical afforestation since 1990, and of baseline afforestation assumed for each country, are shown in Figure 4.7 (EU27), Figure 4.8 (CIS), Figure 4.9 (Canada) and Figure 4.10 (USA). Under the baseline/counterfactual scenario, it was assumed that no forest bioenergy was supplied from the LAM region (i.e. Brazil).

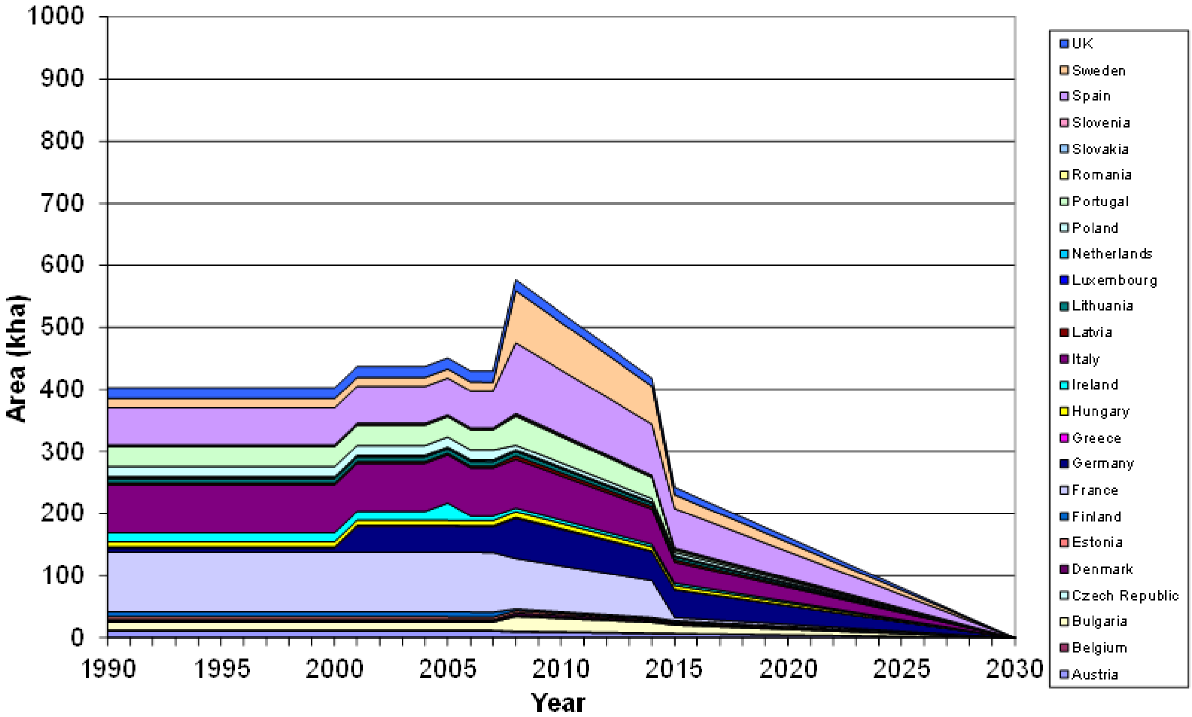

Figure 4.7. Historical and baseline projection of areas afforested in the EU27 region over the period 1990 to 2030, by Member State.

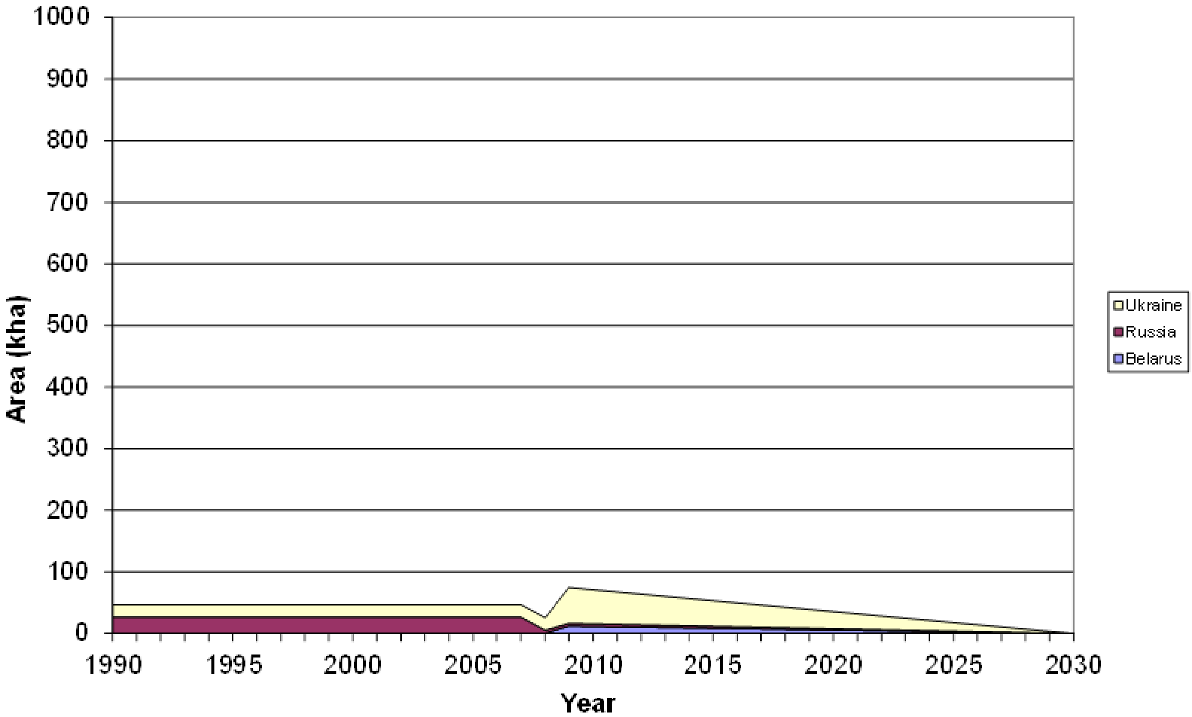

Figure 4.8. Historical and baseline projection of areas afforested in the CIS region over the period 1990 to 2030, by country.

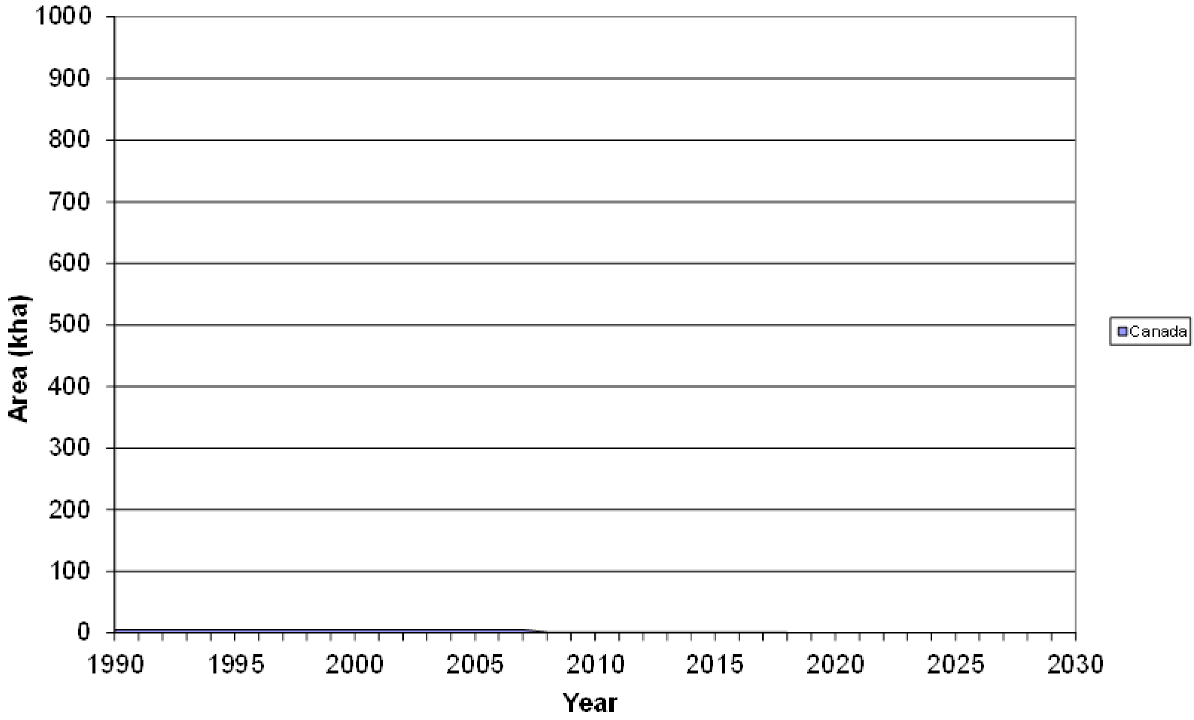

Figure 4.9. Historical and baseline projection of areas afforested in Canada over the period 1990 to 2030.

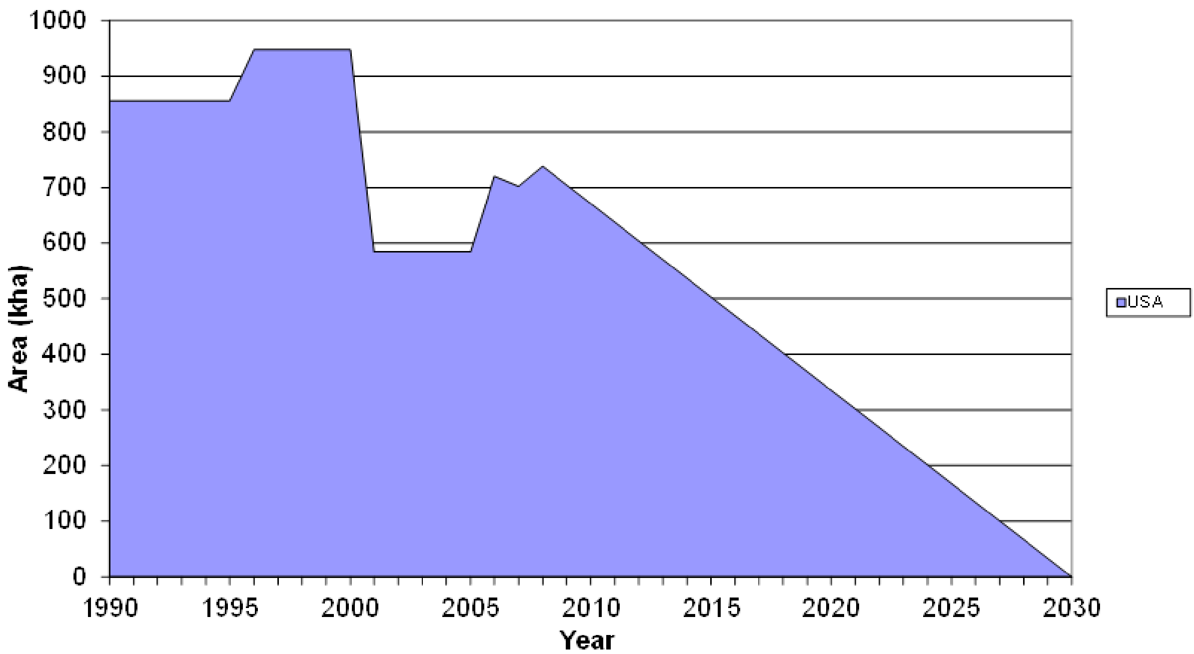

Figure 4.10. Historical and baseline projection of areas afforested in the USA over the period 1990 to 2030.

The data in Figures 4.7 to 4.10 exhibit some fluctuations in annual rates of afforestation. Whilst some of these fluctuations in afforestation rates may seem questionable, these data have typically been reported officially by countries as part of their commitments to the UNFCCC (and the Kyoto Protocol) and represent the best information currently available for most countries.

The tree species and growth rates of afforested areas, and the management prescriptions applied, were allocated on a pro-rata basis, to give the same distribution as for existing forest areas (see Section 4.8.1).

Afforestation for the counterfactual scenario was assumed to take place on former pasture or marginal grassland, rather than arable land. Such an assumption leads to conservative estimates of potential carbon sequestration in soils following afforestation. Afforestation was assumed to take place on both mineral and organic soils, which have contrasting responses to afforestation in terms of soil carbon dynamics (see Appendix 8). The relative proportions of afforested areas on mineral and organic soils was assumed to be constant over time and was based on the observed proportions for each country, as determined from an analysis of soils in relation to forest areas for each country (see Section 4.8.1).

For each Task 2 scenario, the forest modelling exercise explored how forest bioenergy supply, co-production of material products, and consequent impacts on forest carbon stocks and GHG emissions, might depend on approaches taken to forest management and wood use. This was necessary because, as established in Task 1, specific approaches to forest management and the utilisation of wood can have a strong influence on the GHG emissions associated with forest bioenergy (Matthews *et al*., 2014a).

Two contrasting possible approaches to forest management and wood use were developed, referred to as the 'Precautionary' approach and the 'Synergistic' approach. Further details are given in Section 4.8.3. The 'Precautionary' and 'Synergistic' approaches of each scenario included contrasting assumptions about future afforestation (from 2016 onwards).

Assumptions for the 'Precautionary' approach were identical to those for baseline simulations. Because carbon impacts for a scenario are calculated relative to the baseline, this has the effect that any carbon sequestration occurring due to afforestation activities in the baseline scenario is 'factored out'.

Assumptions about afforestation under the 'Synergistic' approach for the CIS region, Canada and the USA were the same as for the 'Precautionary' approach, i.e. no change from the baseline projection. This conservative assumption reflected significant uncertainties about the availability of land for afforestation activities in these regions, particularly with regard to avoiding significant risks of iLUC.

For the EU27 countries, it was assumed that measures could be taken to enhance afforestation rates from 2016 onwards. This enhanced rate of afforestation was taken as three times the rate of afforestation observed in the year 2008. This rate of afforestation was assumed to be constant from 2016 onwards. However, to avoid risks of iLUC, the total afforested area was capped for each EU27 Member State, at 80% of the area of land available for afforestation, as estimated in Task 2 (see Section 4.7.1). This maximum potential area available varied with scenario for each Member State, details are shown in Table 4.4. Assumptions about species composition, growth rates and management of afforested areas were similar to those of the 'Precautionary' approach, except that creation of forests with very low growth rates (all areas with growth rates less than 2 m^3 ha^{-1} yr^{-1} and 50% of areas with growth rates less than 4 m^3 ha^{-1} yr^{-1}) was assumed to be avoided and all of the afforested areas were assumed to be managed for wood production. For the 'Synergistic' approach, it was further assumed that all afforestation post-2015 took place on mineral soils rather than organic soils.

Table 4.4 Estimated land area available for afforestation up to 2050 in the EU27 region by scenario

Member State	Area available (kha)					
	A	B	C1	C2	C3	D
Austria	141	83	126	70	118	144
Belgium	25	73	12	55	5	23
Bulgaria	290	130	214	158	161	283
Czech Republic	14	48	78	35	68	9
Denmark	88	88	88	88	88	88
Estonia	15	15	15	15	15	15
Finland	173	173	173	173	173	173
France	1083	52	942	1153	599	1182
Germany	747	612	788	151	788	804
Greece	9	116	116	116	116	13
Hungary	372	255	321	194	287	366
Ireland	75	74	76	75	76	77
Italy	861	337	769	465	743	882
Latvia	64	64	64	64	64	64
Lithuania	110	59	84	221	65	109
Luxembourg	2	2	2	2	2	2
Netherlands	116	117	117	117	117	117
Poland	2487	2066	2378	2077	2256	2485
Portugal	72	37	68	46	64	73
Romania	778	36	408	135	183	701
Slovakia	46	71	29	71	16	40
Slovenia	18	17	17	17	17	18
Spain	1479	636	1317	836	1276	1496
Sweden	223	223	223	223	223	223
UK	570	118	461	160	427	565

For the LAM region, specifically for the country of Brazil, an assumption was made in the 'Synergistic' approach that the increased demand for bioenergy in the EU27 region would lead to a market response, involving the establishment of high-productivity plantations dedicated to bioenergy production on formerly degraded agricultural land. Studies in

Brazil have reported that the establishment of such plantations has already been occurring to provide biomass for internal consumption (as charcoal, by the Brazilian steel industry), and that the area potentially available for establishment of such plantations is substantial, potentially as much as 200 Mha (ABRAF, 2011; Couto *et al.*, 2011).

The patterns of afforestation assumed for each EU27 Member State are shown in Figure 4.11, based on the example of Scenario B ('Carry on/unconstrained use'). The significant spike in the rate of afforestation between 2016 and 2018 reflects the assumption of a boost in afforestation activities from 2016, but constrained in the case of a number of Member States by the availability of land. The prominent spike in the rate of afforestation between 2016 and 2018 is a distinctly theoretical scenario. However, it is suggested that this represents a maximum level for possible future afforestation activities. In conjunction with the conservative assumptions made about afforestation rates for the 'Precautionary' approach, the two scenarios may be taken to represent the range in possibilities for future afforestation activities in the EU27. Such an approach is appropriate for the sensitivity analysis with respect to forest management activities being carried out here.

It must be noted that, in practice, there may be technical, economic and logistical constraints that would prevent a pronounced boost in afforestation rates over a short period, as represented for the EU27 under the 'Synergistic' approach. In this context, some inertia in the forest sector must be recognised, reflecting the long-term planning needed over the timescales of forest rotations and the investments required to build up infrastructure for forest operations. On the other hand, the peak afforestation rate shown for 2016 in Figure 4.11 represents only a tripling of what are already quite modest afforestation rates reported for 2010 by most Member States, i.e. on average per Member State, an increase from about 17 kha per year to 52 kha per year. It may also be noted that some transformation of land from non-forest cover to forest cover takes place naturally in the EU (as well as elsewhere), for example, when agricultural land is abandoned and then recolonised by regenerating trees. The inclusion of such forest regeneration in the scenarios considered for this project may be open to question. However, as already noted, the rates for afforestation referred to in this project have been formally reported by countries under the UNFCCC, as explicitly representing afforestation activities. These data may have limitations and associated uncertainties, but nevertheless represent the best information currently available.

Further details of the approach taken for the LAM region (i.e. effectively for Brazil) are given in Section 4.8.3. Assumptions for the CIS region, Canada and USA were unchanged from the 'Precautionary' approach.

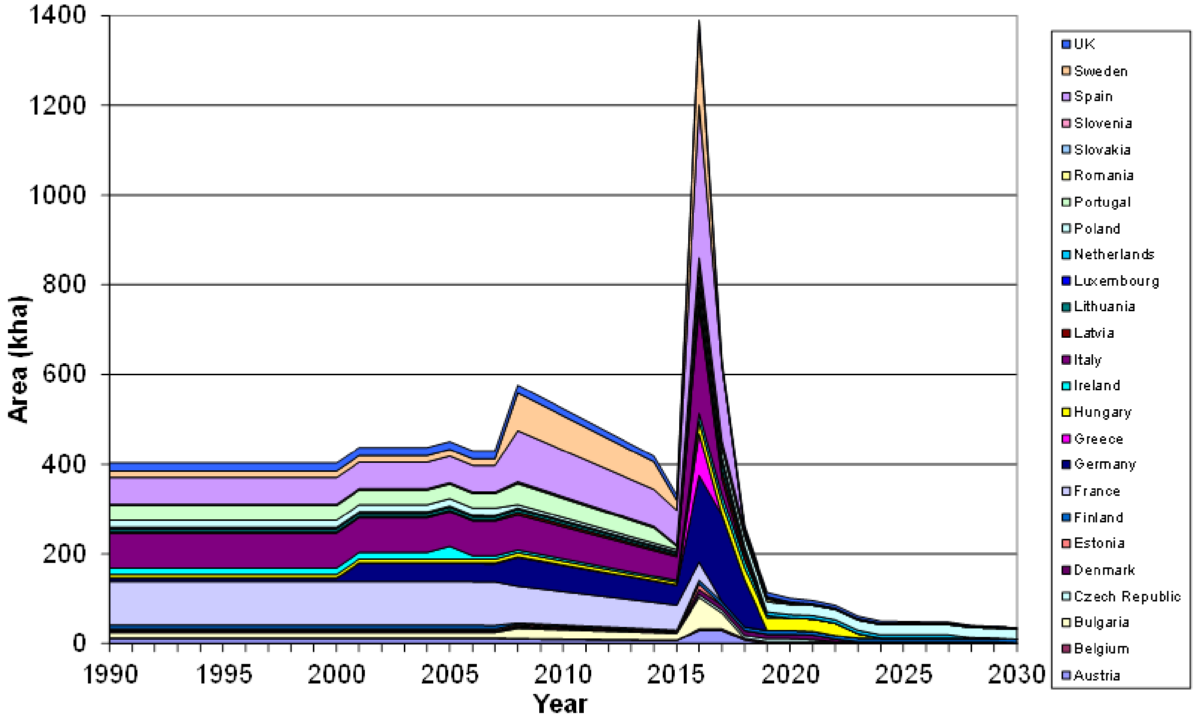

Figure 4.11. Historical and projected areas afforested in the EU27 region over the period 1990 to 2030, by Member State, under the 'Synergistic' approach, as illustrated for Scenario B ('Carry on/unconstrained use').

4.7.3. Deforestation

Baseline estimates of rates of deforestation are available for some countries in the JRC LULUCF tool (Grassi, 2011) and from national reports to the UNFCCC.

Deforestation rates in the forest areas of relevance to this project are generally low (Grassi, 2011), and deforestation is strongly regulated in the EU27 region. Even if rates were to be high, deforestation activities are only of relevance to this project if it is considered that increased demand for bioenergy in the EU27 will lead to a change in current rates of deforestation. For the purpose of this project, it was assumed that increased consumption of forest bioenergy would have negligible effects on current rates of deforestation. It should be noted that existing criteria for defining sustainable forest management and production already strongly discourage wood production associated with deforestation and activities leading to forest degradation.

4.8. Forest management and wood use

4.8.1. Current conditions (counterfactual scenario)

As already explained in Section 4.5.2, information on the management of forest areas is extremely difficult to find, even under baseline conditions. For the purposes of this project, it was necessary to model the management of forest areas in different countries and regions, by inferring rotations and areas under management for production from available statistics on levels of wood production. The first step involved preparing fundamental datasets for each country of interest, classifying forest area by:

- Tree species
- Growth rate
- Characteristic rotation (where relevant).

The discussion in Appendix 9 explains how available datasets were fused to produce the essential input data to the forest modelling exercise. An example of a fused dataset is shown in Table 4.5 for Austria. At this step of the analysis, there was no presumption that all forest areas such as in Table 4.5 were under management for the production of wood. The characteristic rotations shown in the table simply indicate the rotations that would typically be applied to forest areas, if it was the case that these areas were being managed for wood production. It should also be noted that only forest areas reported in forest inventories for countries that were classified as 'available for wood supply' were included in the data-fusion process. For some countries, this meant that significant forest areas classified for protection or amenity use were excluded.

The next step in the analysis involved modelling the areas of forest under management for wood production. The extent of these areas was inferred by an iterative process, which matched levels of wood production simulated by the CARBINE model with those actually reported by countries in international statistics compiled by the FAO for the year 2005 (see Table 4.2). The detailed methodology of this approach is illustrated in Figure 4.12. The FAO statistics on wood production for the year 2005 report values for industrial roundwood production and for wood fuel production. The values reported for countries relevant to this project are shown in Table 4.6. It is apparent from Table 4.6 that, typically, the bulk of wood harvesting is for material wood products. However, there is some limited evidence and there are frequent anecdotal accounts amongst the forestry community that the extent of wood harvesting to supply fuel is under-estimated. This is mainly due to the difficulties in registering local harvesting for domestic supplies of wood fuel. To address this issue, the levels of wood fuel production as reported in FAO statistics were increased, on average, by a factor of 25% with respect to total reported wood production. This is also reflected in the values referred to for 'traditional firewood' in the development of scenarios in Task 2.

Table 4.5 Summary of data on composition of forest areas for the example of Austria

NFI species	Model species	Productivity class (m^3 ha^{-1} yr^{-1})	Basic rotation (years)	Total area (kha)	Area (kha) by age (years)								
					0-10	11-20	21-40	41-60	61-80	81-100	101-140	141-180	> 180
Spruce	NS	14-16	80-100	141.3	1.7	19.9	38.3	21.7	16.9	14.9	17.9	10.0	0.0
	NS	10-12	80-100	565.3	7.0	79.7	153.4	86.6	67.6	59.4	71.7	39.9	0.0
	NS	6-8	80-100	565.3	7.0	79.7	153.4	86.6	67.6	59.4	71.7	39.9	0.0
	NS	4	80-100	141.3	1.7	19.9	38.3	21.7	16.9	14.9	17.9	10.0	0.0
Pine	SP	6-8	80-100	188.4	2.3	26.6	51.1	28.9	22.5	19.8	23.9	13.3	0.0
	SP	4	80-100	235.5	2.9	33.2	63.9	36.1	28.1	24.8	29.9	16.6	0.0
	SP	2	80-100	47.1	0.6	6.6	12.8	7.2	5.6	5.0	6.0	3.3	0.0
Oak	OK	6-8	80-100	43.4	0.7	9.2	8.3	5.2	6.1	5.2	5.6	3.1	0.0
	OK	4	80-100	54.2	0.9	11.5	10.4	6.5	7.6	6.5	6.9	3.9	0.0
	OK	2	80-100	10.8	0.2	2.3	2.1	1.3	1.5	1.3	1.4	0.8	0.0
Beech	BE	6-8	80-100	216.9	3.6	46.0	41.6	26.0	30.4	26.0	27.8	15.6	0.0
	BE	4	80-100	271.1	4.5	57.5	51.9	32.6	38.0	32.5	34.7	19.5	0.0
	BE	2	80-100	54.2	0.9	11.5	10.4	6.5	7.6	6.5	6.9	3.9	0.0
Other broad-leaves	SY	6-8	80-100	57.7	1.0	12.2	11.1	6.9	8.1	6.9	7.4	4.1	0.0
	SY	4	80-100	72.1	1.2	15.3	13.8	8.7	10.1	8.6	9.2	5.2	0.0
	SY	2	80-100	14.4	0.2	3.1	2.8	1.7	2.0	1.7	1.8	1.0	0.0
	AH	6-8	80-100	57.7	1.0	12.2	11.1	6.9	8.1	6.9	7.4	4.1	0.0
	AH	4	80-100	72.1	1.2	15.3	13.8	8.7	10.1	8.6	9.2	5.2	0.0
	AH	2	80-100	14.4	0.2	3.1	2.8	1.7	2.0	1.7	1.8	1.0	0.0
	BI	6-8	80-100	58.1	1.0	12.3	11.1	7.0	8.1	7.0	7.4	4.2	0.0
	BI	4	80-100	72.7	1.2	15.4	13.9	8.7	10.2	8.7	9.3	5.2	0.0
	BI	2	80-100	14.5	0.2	3.1	2.8	1.7	2.0	1.7	1.9	1.0	0.0

NS = Norway spruce; SP = Scots pine; OK = oak; BE = beech; SY = sycamore; AH = ash; BI = birch.

As illustrated in Figure 4.12, the iterative process initially tried to find a proportion of the available forest area that would produce enough harvested wood to match the reported statistics. Forest areas younger than the specified characteristic rotations were included in this initial attempt to find a solution. Older areas were assumed not to be managed for production. The procedure involved allocating the areas with highest growth rate first, then adding areas with progressively lower growth rates until a solution was found. If no solution could be found by this approach, then adjustments were made to the rotations allocated to forest areas, with the aim of increasing long-term wood production. The previous step of allocating forest areas to production was then repeated in a second attempt to find a solution. If this step failed, then the characteristic rotations were re-assigned to the forest areas, and a proportion of the forest areas older than these rotations was also assumed to be under management for production. This involved assigning longer rotations to these older forest areas. The iterative process now tried to find the proportion of older areas of forest that needed to be assigned to management for production in order to obtain a solution. If this step also failed, then the entire iterative process was considered to have failed. However, it proved possible to find a solution for all countries included in the forest modelling for this project. Appendix 10 gives a summary report on the types of solution established for each country.

Table 4.6 Reported production of industrial roundwood and wood fuel for countries for the year 2005

Country	Reported production (1000s of m^3)	
	Industrial roundwood	Wood fuel
Austria	15 488	4 414
Belgium	3 789	600
Bulgaria	3 772	1 938
Czech Republic	16 786	1 487
Denmark	1 231	1 080
Estonia	4 474	1 558
Finland	55 152	5 933
France	33 295	21 533
Germany	58 788	16 548
Greece	689	1 195
Hungary	3 452	2 943
Ireland	2 890	0
Italy	3 499	6 542
Latvia	13 129	2 519
Lithuania	5 446	1 452
Luxembourg	226	14
Netherlands	934	343

Table 4.6 (continued) Reported production of industrial roundwood and wood fuel for countries for the year 2005

Country	Reported production (1000s of m^3)	
	Industrial roundwood	Wood fuel
Poland	35 216	4 218
Portugal	12 578	732
Romania	17 300	10 553
Slovakia	8 260	406
Slovenia	2 368	868
Spain	15 827	1 760
Sweden	75 539	10 826
United Kingdom	9 149	352
EU27	399 277	99 815
Belarus	6 571	1 074
Russian Federation	134 870	50 905
Ukraine	11 387	5 290
CIS	152 828	57 269
Canada	214 057	3 251
United States of America	481 006	34 238

Notes to Table 4.6:

1 Source: FRA2010 (www.fao.org/forestry/fra/fra2010/en/)

2 Reported values for wood fuel have been adjusted to allow for unregistered harvesting of domestic firewood. 50% of the values for the Russian Federation were referred to in modelling of forests, since the scope was restricted to European Russia.

The detailed management prescriptions applied to areas of forest under management for production involved assumptions about whether or not periodic thinning would be practiced. These assumptions reflected regional variations in forest management practices, as shown in Table 4.7.

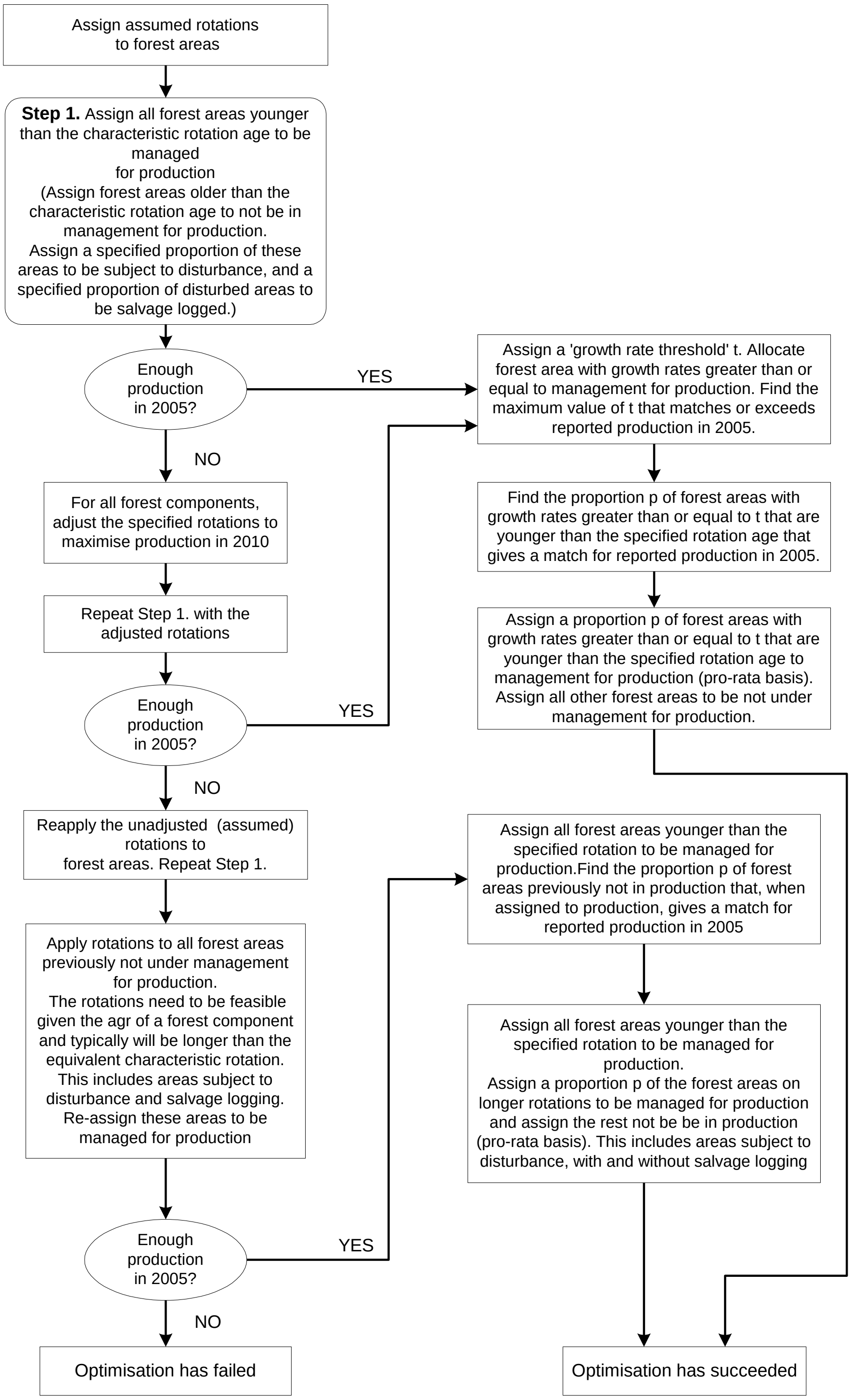

Figure 4.12. Methodology for construction of baseline forestry scenarios.

Table 4.7 Assignment of thinning prescriptions to forest areas managed for production

Country/ region	Heavy thinned	Thinned	Unthinned
EU27	None assigned	Areas with an assigned rotation longer than 40 years	Areas with an assigned rotation of forty years or less
CIS	None assigned	Areas with an assigned rotation of 80 years or less	Areas with an assigned rotation longer than 80 years
Canada	None assigned	Areas with an assigned rotation of 60 years or less	Areas with an assigned rotation longer than 60 years
USA	Pine species with a rotation of 40 years or less	Areas with an assigned rotation of 80 years or less	Areas with an assigned rotation longer than 80 years

Ultimately, the iterative process for establishing baseline simulations was required to meet two criteria:

$$\text{Simulated total volume production} = \text{Reported total volume production}$$

$$\text{Simulated stem volume production} \geq \text{Reported stem volume production}$$

where, for simulated production

$$\text{Total volume} = \text{Stem volume} + \text{Extracted harvest residues}$$

and, for reported production

$$\text{Total volume} = \text{Industrial roundwood} + \text{wood fuel.}$$

According to these criteria, the CARBINE model needed to simulate at least enough stemwood production to match reported industrial roundwood production. Any remaining simulated stemwood production, after allocation to industrial roundwood, contributed towards matching the reported level of wood fuel production, along with a simulated proportion of production from extracted harvest residues. For baseline simulations, aiming to match reported production in 2005, the extent of extraction of harvest residues was assumed as a default to be relatively low, at 15% of the simulated total available resource of harvest residues. This assumption reflected the fact that, traditionally, production of forest bioenergy from harvest residues has not been common practice. However, the proportion selected also aimed to represent the ongoing production of traditional firewood from parts of branchwood, particularly in stands of broadleaved trees.

A final step in the iterative process involved marginal adjustments to the allocation coefficients in the CARBINE model (Figure 4.3), including the coefficient determining extraction of harvest residues, to ensure that CARBINE simulated precisely the mix of quantities of industrial roundwood and wood fuel as reported in FAO statistics (subject to the adjustment of statistics for wood fuel discussed earlier).

The modelling of forests also represented processes of natural disturbance, to the extent that these are relevant to the project. Natural disturbance processes were represented by assigning areas of forest to be felled each year, but without extraction of the felled trees for wood production. An average annual area of disturbance was assumed, which varied with region, based on available information (Seidl *et al*., 2014; B.C. Ministry of Forests, Mines and Lands, 2010). In addition, a proportion of the disturbed forest areas were assumed to be salvage-logged, thus contributing to simulated wood production. The assumed proportion of area salvage-logged also varied with region. The values assumed for parameters representing disturbance and salvage logging are shown in Table 4.8.

No quantitative information was available for CIS or USA; values for Canada were assumed to apply for the USA. Salvage logging was assumed not to be practised in the CIS region.

Table 4.8 Assumed values for parameters determining the simulation of natural disturbance and salvage logging in forests

Country/ region	Annual proportion of forest area subject to disturbance (%)	Proportion of disturbed forest area salvage logged (%)
EU27	0.3	70
CIS	1.3	0
Canada	1.3	25
USA	1.3	25

Sources: Seidl *et al*. (2014); B.C. Ministry of Forests, Mines and Lands (2010).

4.8.2. Forest bioenergy scenarios

The starting point for the modelling of forest scenarios was the set of results produced in Task 2, providing estimates for each scenario, of the biomass to be supplied from forests in the EU27 or imported from regions external to the EU. Figure 4.13 shows the results for the total quantity of forest bioenergy which needs to be supplied under each scenario over the period 2010 to 2050.

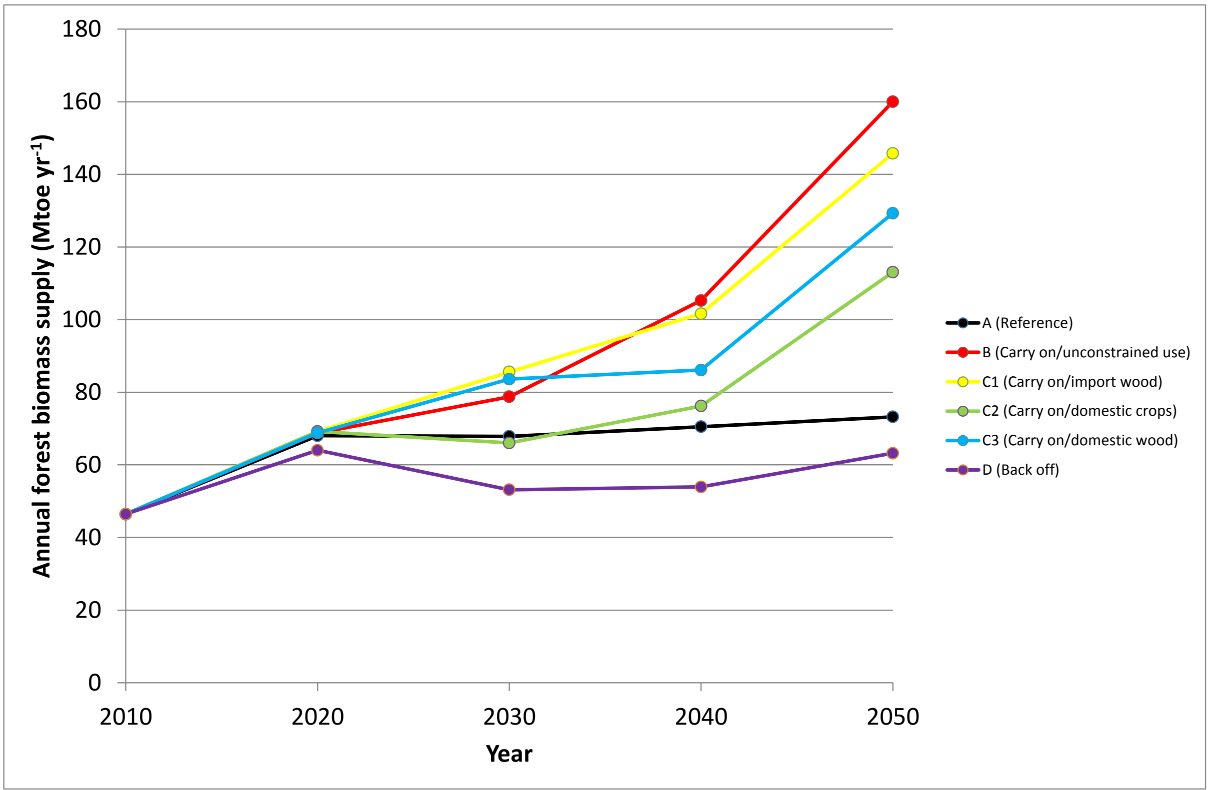

Figure 4.13. Total quantity of forest bioenergy supplied (i.e. total primary forest bioenergy supplied internally and externally) to the EU region for Task 2 scenarios.

As explained in the discussion of Task 2 in Section 3, the levels of total forest bioenergy supply over time under each scenario were simulated using the VTT-TIAM model, based on assumptions and information about biomass requirements, potentials, prices and constraints. Note that the results for forest bioenergy supply, such as illustrated in Figure 4.13, include existing levels of forest bioenergy supply pre-2010, as well as the additional supply above existing levels, as determined for each scenario. The trajectories of total forest bioenergy supply in Figure 4.13 reflect the definition of the various Task 2 scenarios. For example, for the Reference Scenario A, forest bioenergy supply increases between 2010 and 2020, with only modest increases subsequently. This reflects the essential basis of Reference Scenario A, which represents a situation in which existing EU 2020 targets for bioenergy consumption are met, but more ambitious targets are not set post 2020. Similarly, for Scenario D ('Back off'), forest bioenergy supply also increases between 2010 and 2020, but then declines post-2020, reflecting the de-prioritisation of bioenergy under this scenario. The various 'Carry on' Scenarios (B, C1, C2 and C3) all involve increases in bioenergy consumption beyond 2020 targets subsequent to 2020. Consequently, the trajectories for total forest bioenergy supply under these scenarios all continue to increase up to 2050. By 2050, the projected levels of total forest bioenergy supply for the 'Carry on' Scenarios is between 1.5 times to more than double the level projected for Reference Scenario A. The increase is smallest for Scenario C2 ('Carry on/domestic crops'), and in fact levels of forest bioenergy supply under this scenario remain close to levels for Reference Scenario A up to 2040. This reflects the specification of Scenario C2, which emphasises bioenergy supply from agricultural biomass and energy crops. However, after 2040, demand for bioenergy is estimated by VTT-TIAM to be so high that forest bioenergy supply increases markedly up to 2050, even for Scenario C2.

A pronounced increase in the levels of total forest bioenergy supply from some point between 2030 and 2050 is a notable feature of the results for all the 'Carry on' Scenarios, as shown in Table 4.9.

Table 4.9 Projected total annual supply of forest bioenergy, by scenario, for the periods 2020-2030 and 2030-2050

Period	Total annual supply of forest bioenergy (Mtoe yr^{-1})			
	B ('Carry on/ unconstrained use')	C1 ('Carry on/ imported wood')	C2 ('Carry on/ domestic crops')	C3 ('Carry on/ domestic wood')
2020	69	69	69	69
2030	79	86	66	84
2050	160	146	113	129
Change between 2020 and 2030	10	16	-3	15
Change between 2030 and 2050	81	60	47	46

In general, this feature of the Task 2 results for the 'Carry on' Scenarios has quite important implications for forest management and patterns of wood use to deliver the suggested increases in levels of forest bioenergy supply post 2030 (see further discussion in Section 4.10.4). This is also reflected in the final project results for GHG emissions associated with forest bioenergy consumption in the EU region, as discussed in Sections 6.6, 6.7 and 6.9.

The results from Task 2 also give a breakdown of the levels of forest bioenergy supply contributed to the total supply from forests in the EU27 region and for significant regions outside the EU from which forest bioenergy may be imported (i.e. the CIS and LAM regions, Canada and the USA). An example of such results, based on Scenario B ('Carry on/unconstrained use'), is shown in Figure 4.14.

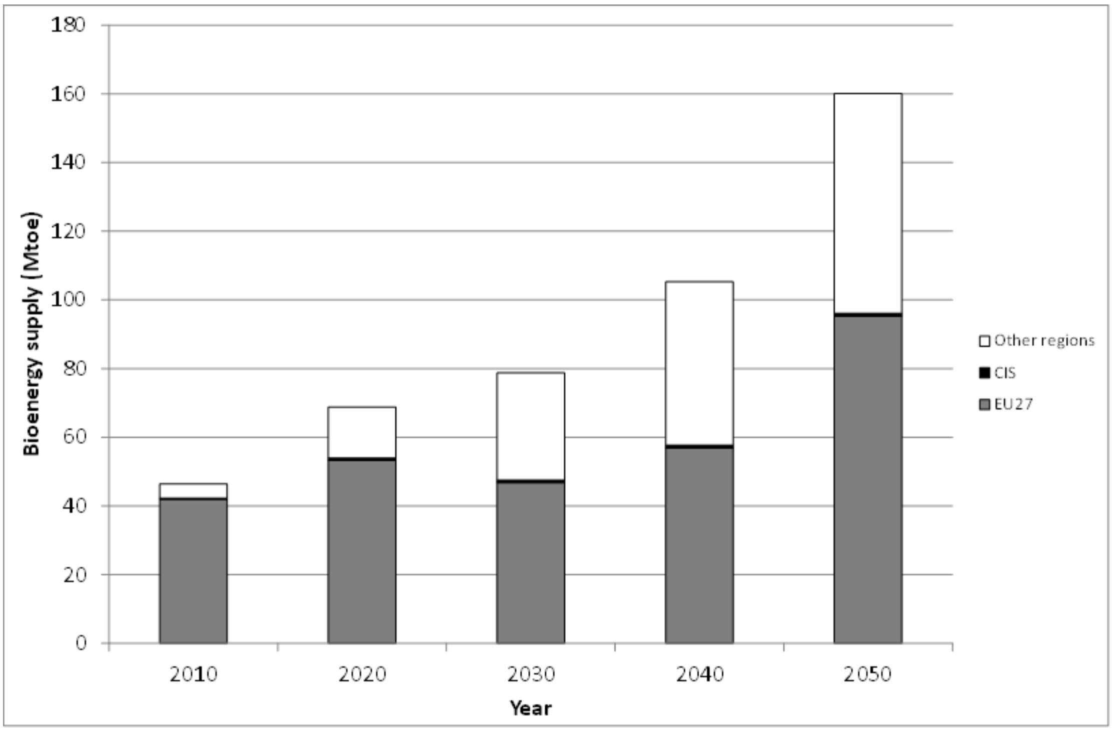

Figure 4.14. Breakdown of contributions to total forest bioenergy supply in the EU region for Scenario B ('Carry on/unconstrained use'), emphasising the contributions from forests in the EU region, CIS region and collectively for other regions.

The contributions to total forest bioenergy supply from within the EU region, and from other regions, were simulated by the VTT-TIAM model. As illustrated in Figure 4.14, in general, the biggest contribution to forest bioenergy supply was estimated to come from within the EU. In contrast, projected levels of supply from the CIS region were consistently relatively very small. Hence, in order to simplify the modelling of forest scenarios in Task 3, the representation of forest bioenergy supplied from the CIS region was slightly simplified, by assuming the same levels of supply over time from this region in all scenarios. The levels of forest bioenergy supply required from other regions external to the EU was then estimated as the difference between the projected total supply and the levels of supply estimated for the EU and CIS regions, as illustrated for Scenario B in Figure 4.14.

As discussed in the consideration of Figure 4.13 and Table 4.9, the various 'Carry on' Scenarios all involve a pronounced increase in the projected level of total forest bioenergy supply from some point after 2030 up to 2050. This is apparent for the example of Scenario B in Figure 4.14. It is also evident that, relatively, the increase in forest bioenergy supply over this period is estimated to be greatest for supply from the EU region. Such an increase would most likely be technically and logistically challenging, and would also have significant implications for impacts on forest carbon stocks in the EU region. Consequently, for the purposes of the modelling in Task 3, an adjustment was made to the original Task 2 results, so that levels of forest bioenergy supply from within the EU region in the period 2040 to 2050 were more consistent with trends in earlier periods for all scenarios. However, this adjustment also had the effect of further emphasising the increase in supply of forest bioenergy from regions outside the EU in the period 2040 to 2050. The effects of the adjustment on projected levels of forest bioenergy supply from the EU, and from other regions, are shown in Figure 4.15 for the example of Scenario B. These adjusted results can be compared with the original results in Figure 4.14. The projected rapid increase in levels of supply from these regions implies significant impacts on forest carbon stocks outside the EU region, as reflected in the final project results and discussed in Sections 6.6, 6.7 and 6.9.

The results for forest bioenergy supply over time to the EU region from 'other regions', such as illustrated in Figure 4.15, are made up of potential contributions from three regions, i.e. Canada, the USA and the LAM region (i.e. effectively Brazil). The VTT-TIAM model simulated the contributions made by these specific regions for each scenario. However, it was apparent that these detailed results were extremely variable, because they were highly sensitive to assumptions about potential biomass availability and, more particularly, relative prices of biomass of different regional origins. Consequently, a simplified approach was adopted to estimate these contributions. This approach included an investigation of the sensitivity to assumptions about specific origins of forest bioenergy imported into the EU region.

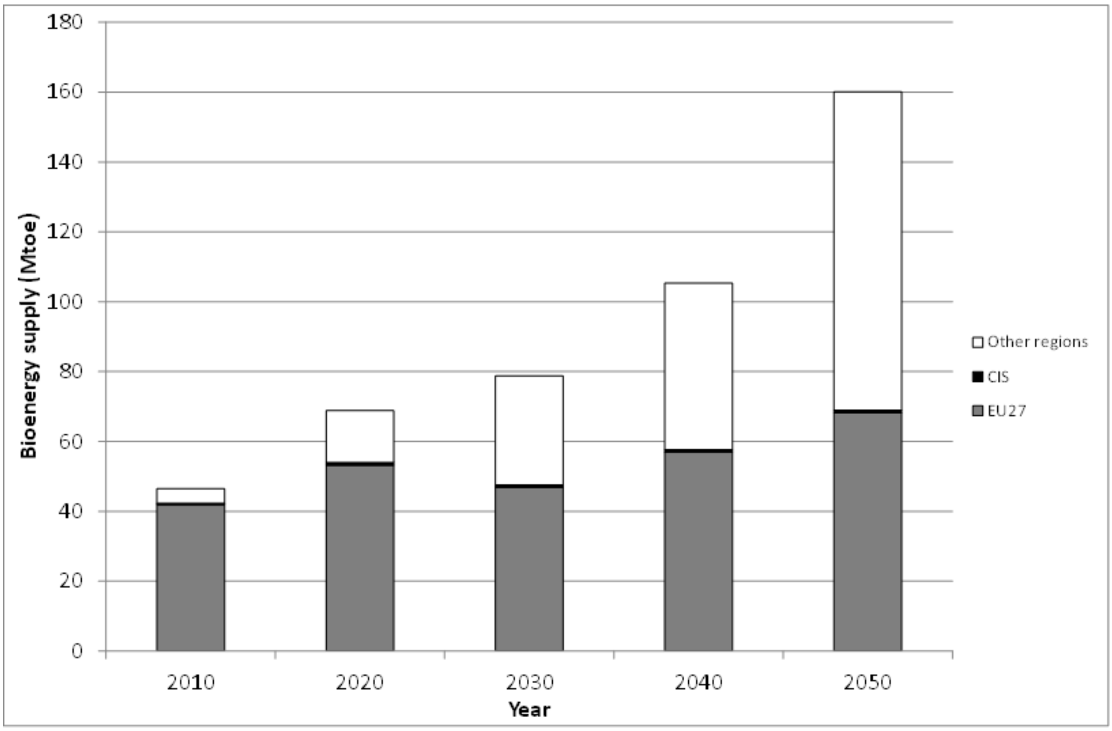

Figure 4.15. Adjusted breakdown of contributions to total forest bioenergy supply in the EU region for Scenario B ('Carry on/unconstrained use'), emphasising the contributions from forests in the EU region, CIS region and collectively for other regions.

Two possible cases were thus defined for the importation of forest bioenergy to the EU for each scenario. These two cases formed, respectively, part of the definitions for the 'Precautionary' approach and 'Synergistic' approach to changes in forest management and patterns of wood use to supply additional quantities of forest bioenergy:

1. Limited supply from the CIS region (see earlier discussion), 50% of total remaining imported forest bioenergy supply from Canada, 50% of total imported supply from the USA, no supply from the LAM region (i.e. effectively Brazil)
2. Limited supply from the CIS region (see earlier discussion); before 2020, 50% of total remaining imported forest bioenergy supply from Canada, 50% of total imported supply from the USA, no supply from the LAM region; from 2020 onwards, 33.3% of total imported forest bioenergy supply from Canada, 33.3% of total imported supply from the USA, 33.3% of total imported supply from the LAM region (i.e. effectively Brazil).

Figures 4.16 and 4.17 show the levels of forest bioenergy supply to EU from all regions considered in this project, for the example of Scenario B ('Carry on/unconstrained use'), respectively for the two cases for importation of biomass defined above.

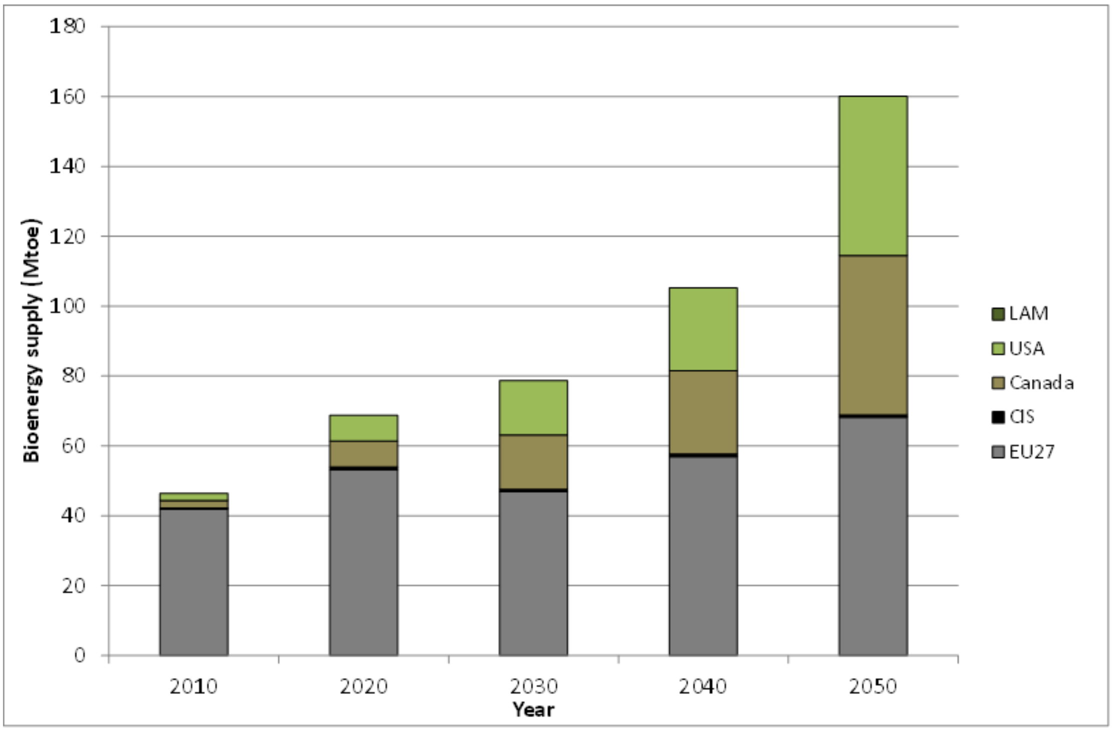

Figure 4.16. Detailed breakdown of contributions to total forest bioenergy supply in the EU region for Scenario B ('Carry on/unconstrained use'), based on assumptions for 'Precautionary' approach.

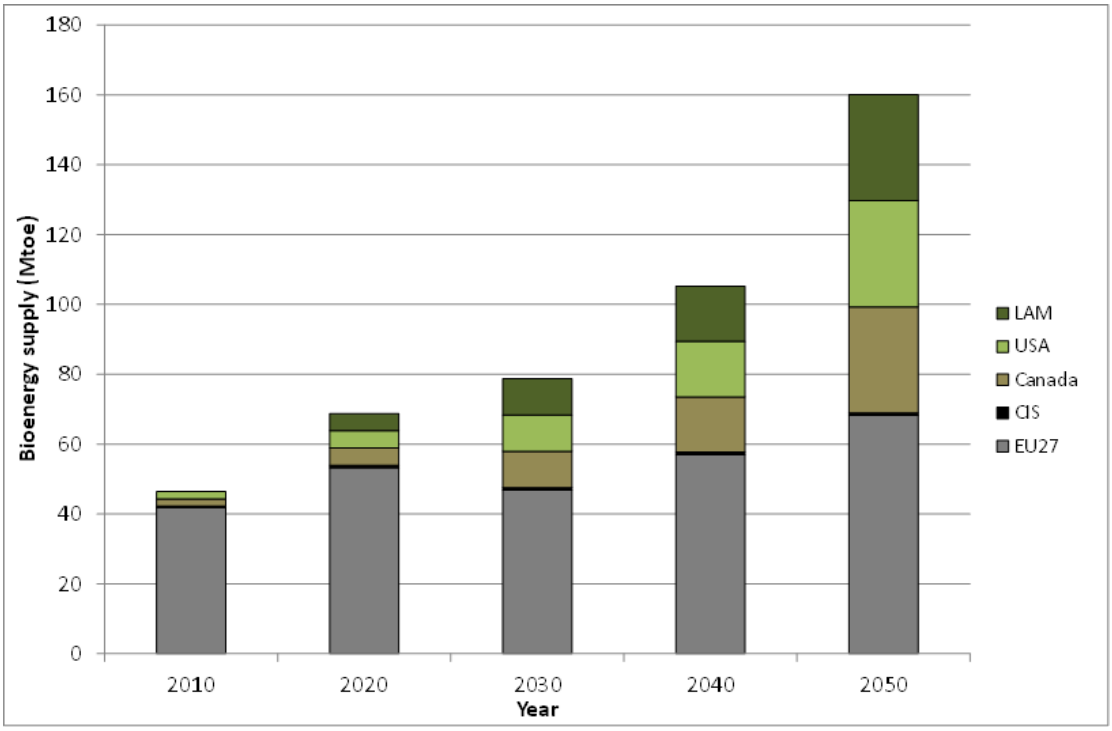

Figure 4.17. Detailed breakdown of contributions to total forest bioenergy supply in the EU region for Scenario B ('Carry on/unconstrained use'), based on assumptions for 'Synergistic' approach.

The methodology adopted for constructing forest bioenergy scenarios involved an iterative process. The CARBINE model was first applied to simulate levels of wood production for a baseline or counterfactual scenario. The levels of forest bioenergy production simulated by CARBINE were then compared with the levels effectively specified in the results for scenarios from Task 2. If the simulated levels of forest bioenergy supply were lower than the required levels according to the Task 2 results, then changes were made to forest management and patterns of wood utilisation as represented in CARBINE, to increase the simulated level of supply until the required level was met. This iterative process is illustrated in Figure 4.18. The actual computational process of matching simulated levels of forest bioenergy supply to the levels suggested for each scenario, based on the results of Task 2, was complex and intensive, because the match needed to be near exact.

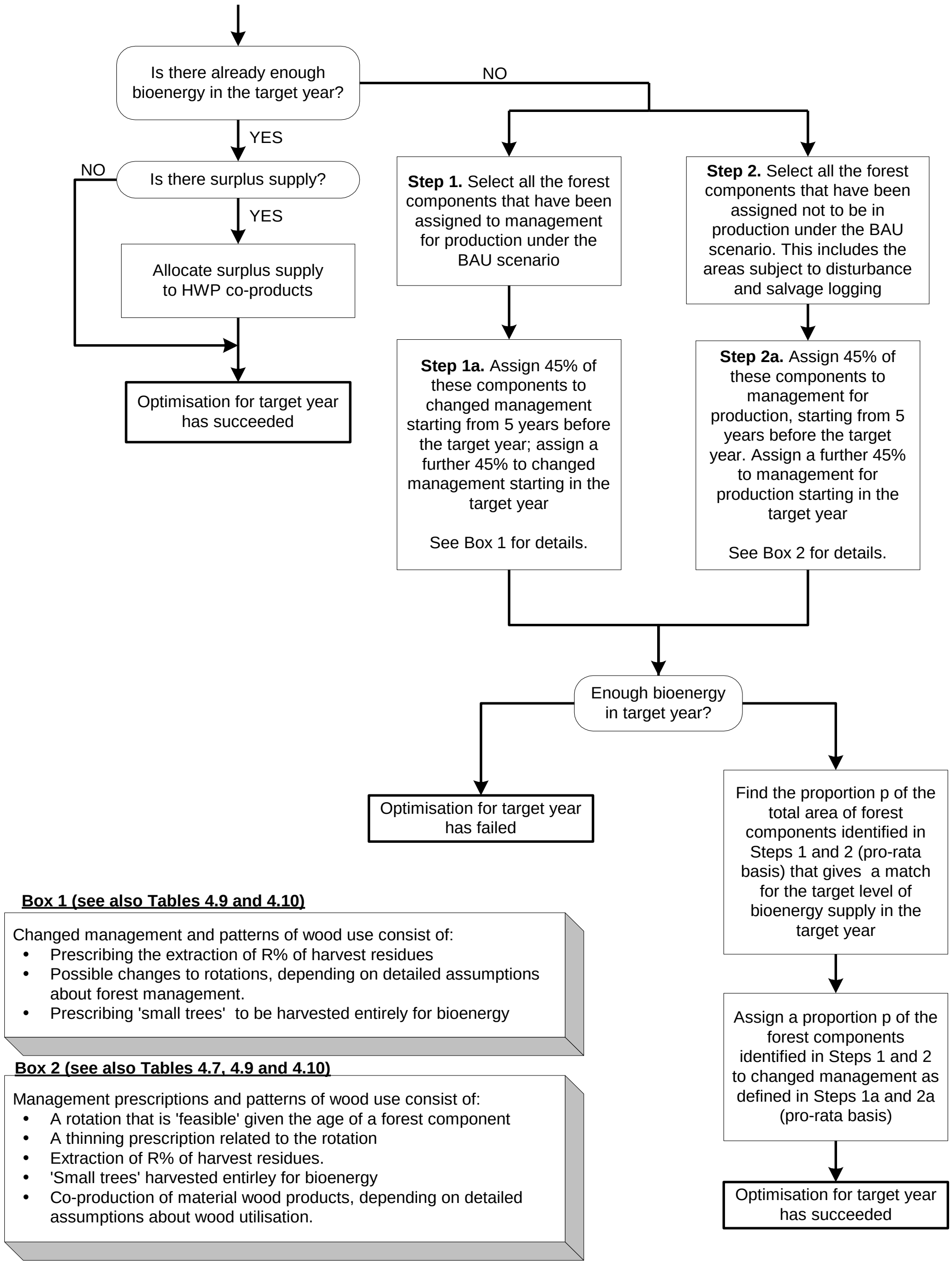

Figure 4.18. Methodology for construction of bioenergy scenarios.

The iterative process for matching levels of forest bioenergy supply was different for the supply from the EU region, compared with for the supply to the EU from external regions. This was necessary because, typically, supplies of forest bioenergy produced in the EU region would also be consumed in the EU region. However, typically for an external region, only some of the forest bioenergy produced would be supplied to the EU. Results from Task 2 for levels of forest bioenergy supply from within the EU region included baseline levels of supply. Hence, when matching results from CARBINE simulations, this was based on total simulated levels of forest bioenergy supply. In other words, the matching process involved comparing absolute quantities of simulated forest bioenergy supply with the level specified in Task 2 results, rather than considering simulations that were marginal to the baseline or counterfactual scenario. As a simplification, it was assumed that all forest bioenergy produced in the EU region was also consumed in the EU region. In contrast, results from Task 2 for levels of forest bioenergy supply to the EU from external regions did not include levels of forest bioenergy supply for consumption elsewhere, including domestically within the producer region. To allow for this, it was first assumed that forest bioenergy produced by an external region in 2005 was consumed entirely outside the EU region. These results were available in internationally reported statistics and simulated levels of forest bioenergy supply for baseline or counterfactual scenarios had been matched to these reported results (see Section 4.8.1). For forest scenarios, CARBINE simulations were required to match the level of forest bioenergy supply for 2010 as already simulated under a baseline scenario, plus the quantity specified for the region in the relevant Task 2 results for each scenario. In this way, the matching process for imported supplies of forest bioenergy involved comparing marginal quantities of simulated forest bioenergy supply with the levels specified in Task 2 results for each scenario.

4.8.3. Forest management approaches

At each step in the iterative process described in Section 4.8.2, changes were made to the forest management prescriptions and patterns of wood use represented in the CARBINE model, to increase or decrease the simulated levels of forest bioenergy production. In reality, the changes involved are likely to be multiple and complex, as has been discussed in the Task 1 report for this project (Matthews *et al.*, 2014a), and summarised in Section 2 of this report. In particular, the decision tree in Figures 2.1a to 2.1d (see Section 2.4) describes systematically the many possible options for approaches to forest management and the utilisation of harvested wood that might be involved in forest bioenergy supply. For the purposes of this project, it was considered important that the modelling of forests in Task 3 explored the sensitivity of GHG emissions associated with forest bioenergy to specific approaches to forest management and wood utilisation. It was not possible within the scope of this project to model all possible cases of such approaches. Hence, two contrasting approaches were defined, referred to as the 'Precautionary' approach and the 'Synergistic' approach. In broad terms, with reference to the decision tree in Figures 2.1a to 2.1d, the 'Precautionary' approach involved assumptions that implied the discouragement or de-prioritisation of higher risk options for the production of forest bioenergy. The 'Synergistic' approach included the principles of the 'Precautionary' approach, but also involved assumptions implying the encouragement or prioritisation of lower risks options for the production of forest bioenergy. Further details of the assumptions made under the 'Precautionary' and 'Synergistic' approaches are given in Table 4.9.

For the definition of the 'Precautionary' approach to forest management and wood use, it was considered important not to make unduly optimistic or pessimistic assumptions about the types of forest and wood feedstock involved in the supply of forest biomass for energy to the EU. Specifically:

- Reference was made to data on forest areas reported in National Forest Inventories, for a range of countries of relevance to this study.
- It was assumed that biomass supply for energy could be produced from forests in all geographical areas of countries and regions included in this study, and all forest types represented in National Forest Inventories as available for wood production, essentially on a proportional basis (subject to some limited constraints, see subsequent discussion and Section 4.8.4). This means that forest types supplying biomass for energy, as represented in the project scenarios, comprise a range of tree species (coniferous and broadleaved) and growth rates, either already under management for production, or with management for production introduced in response to the increased demand for forest bioenergy.
- It was also assumed that a range of wood feedstocks would be involved in the supply of biomass for energy. Essentially, the bigger the magnitude of the potential for supply of the feedstock, the greater the use within the project scenarios (see Section 4.8.4). However, as explained later in this discussion, some constraints were applied.

It follows that assumptions made for the 'Precautionary' approach about forest biomass supply for use as energy in the EU did not favour either particularly 'good' or particularly 'bad' types of forest or wood feedstocks, covering all possible types that might be involved in such supply, according to their potentials (subject to a few relevant constraints).

These assumptions reflect the purpose of this project, in making a general, high-level and strategic assessment of potential impacts on GHG emissions, arising from possible EU policies towards the future consumption of biomass for energy in the EU, where some of this biomass will consist of forest biomass from sources within and external to the EU, without unduly emphasising or preferring specific sources of relevant forest biomass, in terms of forest types or feedstocks.

In essence, the changes to forest management assumed under the 'Precautionary' approach included:

- The introduction of management for production (involving felling and possibly thinning) in forest areas not previously managed for production. This also involved an element of increased salvage logging.
- The increased extraction of harvest residues, and changes in patterns of wood use, in a proportion of forest areas managed for production.

The detailed assumptions about the extraction of harvest residues varied with scenario, as shown in Table 4.10.

The extraction of harvest residues from forest sites needs to be undertaken with care because this practice can have a detrimental effect, not only on carbon stocks in forest litter but also carbon dynamics in forest soils (see for example Diochon *et al*., 2009; Johnson *et al*., 2009), and on the nutrient regime of the soil (see for example Christophel *et al*., 2013, 2015). In the case of impacts on soil nutrients, this is particularly the case if foliage is extracted as part of the residues and, ideally, this practice should be avoided. The risks of negative impacts on the nutrient status of soils, that could be associated with the excessive removal of harvest residues, are a cause for concern (Jonard *et al*., 2015). Ideally, these impacts, or the impacts of any activities to remediate nutrient deficiencies (e.g. through fertiliser application or redistribution of wood ash in forest areas) should be quantified (Paillet *et al*., 2013). However, this approach has not been taken in this project. Instead, in this project, the issue has been addressed by suggesting relatively low maximum percentages for the extraction of harvest residues for use as bioenergy (i.e. between 30% and 50%, see Table 4.10). Furthermore, as explained in Note 3 to Table 4.10, it is also important to understand that the percentages for extraction of harvest residues indicated in Table 4.10 are not applied over the whole forest area for a given region, or even over the whole area of forest managed for wood production. The percentages are only applied to the proportion of forest areas for which management is changed to produce additional forest bioenergy (see Figure 4.18). For example, suppose the percentage specified (as in Table 4.10) for the extraction of harvest residues is 40%. Suppose also that the modelling of baseline forest management in a particular country has estimated that a forest area of 15 Mha is currently under management for production. Now, suppose further that the optimisation procedure illustrated in Figure 4.18 allocates a proportion 60% of this area to be under changed management for increased bioenergy production. Then, 40% of harvest residues would be allocated for extraction from 60% of the 15 Mha area of forest. This implies that 24% of the available harvest residues in this area would be assigned to be extracted. This represents an average percentage – in reality, a greater proportion of harvest residues would be extracted in some areas (where risks are lower), whilst smaller proportions of residues (possibly none) would be extracted in other areas.

There are also other reasons for placing constraints on the contributions made by harvest residues to forest bioenergy supply. Specifically, as explained in Note 2 to Table 4.10, there can be issues with the quality of feedstock for forest bioenergy (notably in the case of wood pellets), if the contribution made by harvest residues is too great. Hence, the proportion of forest bioenergy contributed by harvest residues to total forest bioenergy supply was capped as described in Note 2 to Table 4.10. This limits further the extent of extraction of harvest resides across forest areas. The fact remains that the increased extraction of harvest residues may lead to nutrient deficiencies in some forest areas, which would have consequences for the future productivity of affected forest areas. One option for remediating such impacts could involve the redistribution of wood ash produced from the burning of forest bioenergy, back to affected forest land.

Other assumed changes to patterns of wood use involved:

- Prescribing 'small trees' to be harvested entirely for bioenergy (this might also involve additional early thinnings in some forest areas)
- Limited co-production of material wood products from forest areas where management for production was introduced (see Table 4.9).

For the purposes of this project, 'small trees' were defined in terms of the average proportion of potential sawlog material contained in the stemwood of trees harvested from a stand through thinning or felling. To count as small trees, harvested stemwood needed to contain, on average, less than a specified threshold proportion of sawlog material. The detailed assumptions about the threshold varied with scenario, as shown in Table 4.10. Within the CARBINE model, different definitions are referred to for coniferous and broadleaved stands, when determining the quantity of sawlog material within the stemwood of harvested trees (see Section 4.4.5).

As with the modelling of the extraction of harvest residues, it is important to understand that the percentages assigned for removal of small trees are not applied over the whole forest area for a given region, nor even over the whole area of forest managed for wood production. The percentages are only applied to the proportion of forest areas for which management is changed to produce additional forest bioenergy (see Figure 4.18). For example, suppose the modelling of baseline forest management in a particular country has estimated that a forest area of 15 Mha is currently under management for production. Suppose also that the optimisation procedure illustrated in Figure 4.18 allocates a proportion 60% of this area to be under changed management for increased bioenergy production. Then, a specified threshold of 5% for identifying "small trees" in thinnings for harvesting for use as forest bioenergy would apply to 60% of the forest area of 15 Mha, or 9 Mha.

Table 4.9 Summary description of 'Precautionary' and 'Synergistic' approaches to forest management and patterns of wood use involved in the supply of additional forest bioenergy, in comparison to the baseline/counterfactual case

Factor	Counterfactual	'Precautionary' approach	'Synergistic' approach
Growth rate	Prioritisation of management for production from forest areas with higher growth rates	No prioritisation of forest areas for management for additional production above baseline with respect to growth rate	Exclusion of forest areas with very low growth rates from management for additional production above baseline. (Areas with very low growth rates were defined as 100% of area with growth rate 2 $m^3\ ha^{-1}\ yr^{-1}$ and 50% of area with growth rate 4 $m^3\ ha^{-1}\ yr^{-1}$.)
Rate of afforestation from 2016 onwards (see discussion in Section 4.7.2)	EU, CIS, Canada and USA: Progressive reduction in currently reported rates until zero in 2030 LAM (Brazil)[1]: Abandoned and degraded agricultural land remains degraded	No change from counterfactual	EU only: Enhanced rates from 2016 to 2030, zero thereafter. Avoid organic soils. LAM: Afforestation of degraded agricultural land in Brazil to meet biomass supply implied by VTT-TIAM. CIS, Canada, USA: No change from counterfactual (note that this is a conservative assumption due to lack of information on iLUC risks)
Rate of deforestation from 2016 onwards (see discussion in Section 4.7.3)	Any wood produced excluded from potential supply	No change from counterfactual	No change from counterfactual
Adjustments to forest management	No adjustments	See below	Where relevant, extension of rotations to enrich growing stock and carbon stocks as well as increase long-term productivity.
Extraction of harvest residues	Not extracted (left in forest, note that this is a conservative assumption, burning of residues could have been assumed, at least in some cases)	Proportion extracted (see Table 4.10, remainder left in forest	

Table 4.9 (continued) Summary description of 'Precautionary' and 'Synergistic' approaches to forest management and patterns of wood use involved in the supply of additional forest bioenergy, in comparison to the baseline/counterfactual case

Factor	Counterfactual	'Precautionary' approach	'Synergistic' approach
Utilisation of small trees	Co-production of bioenergy and materials. No extraction of branchwood	Bioenergy as sole product, including 90% of branch wood (but see Table 4.10)	
Utilisation of wood from forest areas not previously managed for production (not subject to natural disturbance, disturbed and not salvage-logged, disturbed and salvage-logged)	No active management for production	Introduction of harvesting in a proportion of these forest areas, no active management in the remainder. Harvesting includes extraction of harvest residues and utilisation of small trees for bioenergy only (see above)	
Co-production of bioenergy with material wood products when harvesting is introduced in forest areas not previously managed for production	No production except for salvage-logging	Limited co-production of material wood products, i.e. all small roundwood used for bioenergy and, for sawlogs, only wood suitable for use as sawn wood	Emphasis on co-production of material wood products, i.e. small roundwood and sawlogs used for a combination of bioenergy and materials.

Notes to Table 4.9:

1 It should be noted that other possibilities for the counterfactual land/wood use exist, including continued abandonment, but with recolonisation with secondary forest, or creation of plantation forests but to increase supply to other industries (e.g. charcoal for steel in Brazil). Assessments based on these counterfactuals for land/wood use would most likely lead to very different results for impacts on biogenic carbon emissions/non-biogenic GHG emissions. However, note that very conservative assumptions were made in this project when estimating carbon sequestration through the modelling of forest carbon stock dynamics in new areas of Brazilian plantation forests.

Table 4.10 Summary of assumptions on extraction of harvest residues and utilisation of small trees for forest bioenergy

Scenario	Proportion of harvest residues extracted[1,2] (%)	Threshold sawlog proportion of stem volume for determining 'small trees' (%)	Comments
A	30	5	These are the default assumptions. The percentage of harvest residues extracted is assumed to apply on average, where increased extraction is introduced. The value is quite conservative. The threshold for small trees effectively limits the use of whole trees to those with negligible sawlog volume.
B	40	5	The contribution due to harvest residues was increased to help mitigate the impacts of relatively high forest bioenergy supply from forests, as implied by several 'Carry on' Scenarios.
C1	30	5	The contribution due to harvest residues was not increased above the default for this scenario, due to the emphasis on forest bioenergy imported into the EU region. The preferred form for long-distance transport of forest bioenergy is as wood pellets. These are difficult to manufacture if the proportion of harvest residues forming the feedstock is too great.
C2	40	5	See Scenario B
C3	50	10	The contribution due to harvest residues was increased, and the threshold for determining the contribution from small trees was relaxed, to help mitigate the impacts of relatively high forest bioenergy supply from forests, as implied by several 'Carry on' Scenarios. These adjustments place more emphasis on increasing extraction of wood for forest bioenergy from forest areas already being managed for production, and less emphasis on the introduction of management for production in other forest areas.
D	30	5	See Scenario A

Notes to Table 4.10:

1 From 2011 up to 2015, this percentage was set to the value of 30%, for all scenarios. (Note that the default percentage for baseline simulations was 15%.)

2 Despite the application of the percentages for extraction of harvest residues shown in the table, the proportion of forest bioenergy contributed by harvest residues to total forest bioenergy supply was capped not to exceed a value 10% greater than estimated for the year 2010. Thus, if the contribution in 2010 was 12%, future contributions were capped at 22%. The cap was applied in recognition that there can be issues with the quality of feedstock if the contribution made by harvest residues is too great.

In defining the detailed assumptions for both the 'Precautionary' and 'Synergistic' approaches, a key assumption was made that sustainability criteria would preclude certain activities with significant negative impacts on forest carbons stocks and forest growing stock in general. Such precluded activities included permanent deforestation and the replacement of areas of high forest with plantation forests grown on very short rotations. This approach is consistent with the reference to sustainability criteria in the development of the scenarios for this project, as described in Sections 2.3.2 and 2.5.

At the same time, the specification of the 'Precautionary' approach still includes some forest management and wood use options that would be identified by the decision tree as high risk. These are included as part of the definition of a plausible combination of changes in activities that might take place in the absence of stricter controls on forest management and wood production (i.e. beyond existing criteria already applied more generally in forestry), notably:

- No restrictions are placed on production from forest areas with low growth rates
- Relatively limited co-production of material wood products alongside forest bioenergy production, in those areas where management for wood production is introduced where previously this was not practiced.

The 'Synergistic' approach was designed to represent a situation in which additional policies or measures may be taken that actively support the production of forest bioenergy with negative, relatively low or moderate risks of significant associated GHG emissions. Some of these actions may also be market-driven to some extent, for example, as described above in the case of afforestation in the LAM region (specifically Brazil), as described below.

The additional positive changes to forest management assumed under the 'Synergistic' approach included:

- Avoiding the introduction of additional harvesting in forest areas with very low growth rates, to protect against slow recovery of carbon stocks after harvesting
- In the EU27 region only, enhanced rates of afforestation post 2015, de-prioritising creation of forest areas with very low growth rates or on organic soils (see Section 4.7.2)
- Where feasible, conservation and enhancement of forest carbon stocks alongside increased harvesting to produce forest bioenergy and materials, through adjustments to existing rotations applied to forest areas managed for production.

Additionally under the 'Synergistic' approach, in forest areas where management for production was introduced, much greater emphasis was placed on co-production of material wood products alongside production of forest bioenergy when compared with the 'Precautionary' approach (see Table 4.9).

The 'Synergistic' approach also involved different assumptions about the supply of forest bioenergy to the EU from external regions, as already discussed in Section 4.8.2.

Specifically, for the LAM region (i.e. effectively Brazil), an assumption was made in the 'Synergistic' approach that the increased demand for bioenergy in the EU27 region would lead to a market response, involving the establishment of high-productivity plantations dedicated to bioenergy production on formerly degraded agricultural land. The levels and rates of afforestation in the LAM region were determined to ensure that levels of forest bioenergy supply required from the LAM region under each Task 2 scenario could be met (see start of Section 4.8, in particular the discussion of Figures 4.16 and 4.17). This required assumptions to be made about the potential productivity of plantations in the LAM region, and the rotations applied. It was assumed that such plantations would typically involve the establishment of eucalyptus stands with potential stem volume productivity over a 4-year rotation of 40 m^3 ha^{-1} yr^{-1}. Typically, eucalyptus wood has a density of around 0.5 odt m^{-3}; a density of 0.49 odt m^{-3} was assumed for the parameterisation of the CARBINE model. Forest bioenergy production was assumed to involve the harvesting of all stemwood with an efficiency of 90%, plus the harvesting of 90% of associated branchwood, roughly giving a further 30% of supply over stemwood production. Based on these assumptions, it was possible to calculate the total areas and rates of afforestation for the LAM region as illustrated by the example in Box 4.1. The forest areas involved are significant (e.g., by 2050, ranging from 300 kha for Scenario D, 'Back off', to nearly 3 Mha for Scenario B, 'Carry on/unconstrained use'). However, studies in Brazil have reported that the establishment of such plantations has already been occurring to provide biomass for internal consumption (ABRAF, 2011; Couto *et al.*, 2011; Kröger, 2012), and that the area potentially available for establishment of such plantations is substantial, i.e. of the order of 200 million hectares (Couto *et al.*, 2011). Furthermore, the rates of afforestation estimated for the scenarios in this project are easily consistent with recently observed levels.

Box 4.1 Example of calculation of areas afforested in the LAM region (Brazil) to meet specified levels of forest bioenergy supply to the EU region

Based on Couto *et al.* (2011), it was assumed that eucalyptus plantations in Brazil would yield 40 m^3 ha^{-1} yr^{-1} stem volume on a four year rotation. This equates to 160 m^3 ha^{-1} standing stem volume after four years.

The density of eucalyptus wood is typically about 0.5 odt m^{-3} (Lavers, 1983; Couto *et al.*, 2011). A value of 0.49 odt m^{-3} was referred to in the CARBINE model. This implies standing stem biomass after four years of 160 × 0.49 = 78.4 odt ha^{-1}.

The CARBINE model estimated a further 32% of biomass additional to stemwood in branchwood after four years. This gives a total standing woody biomass above ground of 78.4 × 1.32 =103.49 odt ha^{-1}.

It was assumed that standing woody biomass was harvested, without roots, with an efficiency of 90%, giving a yield after four years of 103.49 × 0.9 = 93.14 odt ha^{-1}.

Assuming a lower heating value for wood of 18.6 GJ odt^{-1}, the energy supplied by 1 hectare of eucalyptus plantation on a four-year rotation is 93.14 × 18.6 = 1732.40 GJ ha^{-1}, or 0.001732 PJ ha^{-1}, or 0.00004138 Mtoe ha^{-1}.

It follows that the area of eucalyptus plantation required to supply 1 Mtoe of forest bioenergy in a given year is 1 ÷ 0.00004138 = 24,168 ha.

Under all scenarios, for the 'Synergistic' approach, the quantity of forest bioenergy required from Brazil by 2020 is 4.934 Mtoe. The area of eucalyptus plantation required to supply this energy in one year is 4.934 × 24,168 = 119,245 ha. The eucalyptus plantations take four years to produce this yield, hence, this area needs to be planted for four years in order to maintain supply at the specified level. To supply this energy on a constant basis from 2020 onwards thus requires 119,245 ha of eucalyptus plantations to be planted in each of the years 2016, 2017, 2018 and 2019.

The representation of possible afforestation in the LAM region (i.e. Brazil), as part of the 'Synergistic' approach to forest management and wood use, but not as part of the 'Precautionary' approach, is consistent with the definitions of these two approaches. This is because the impacts on carbon stocks associated with afforestation of abandoned and degraded agricultural land in Brazil is likely to be very positive (i.e. enhancement of carbon stocks). However, it is unclear to what extent a market-driven response to demand for bioenergy in the EU, involving significant afforestation in Brazil, would actually occur. Given this uncertainty, and possible contentiousness associated with contributions from the LAM region, or more specifically Brazil, assumptions were made that limited the supply of forest bioenergy from such sources, e.g. typically around 15%

of total forest bioenergy consumption in the EU (see for example Figure 4.17, Section 4.8.2).

In general, a conservative approach was taken to representing a potential contribution from plantation forests in Brazil to forest bioenergy consumed in the EU region. In addition to the assumptions just described, the potentially positive impacts of such afforestation on litter and soil carbon stocks were excluded from the results referred to in estimating GHG emissions associated with forest bioenergy supplied from Brazil. Essentially, potential contributions to carbon sequestration from litter and soil were assumed, conservatively, to be zero.

4.8.4. Representation of forest management approaches in different regions

As explained in Section 4.8.3, at each step in the iterative process described in Section 4.8.2, changes were made to the forest management prescriptions and patterns of wood use, represented in the CARBINE model, to increase or decrease the simulated levels of forest bioenergy production. The discussion in Section 4.8.3 has also explained the types of changes made to assumptions about future forest management and patterns of wood utilisation, to simulate the increased levels of forest bioenergy supply, as represented in the scenarios developed in this project. Typically, in order to meet target levels of forest bioenergy supply, the iterative process described in Section 4.8.2 involved:

- Increasing the extraction of wood in a proportion of the area of forest already under management for wood production ('increased extraction')
- Re-assigning a proportion of the area of forest not currently under management for wood production, to introduce management for production ('introduced production').

The relative areas assigned for increased extraction and for introduced production depended on the existing characteristics of the current management of forest areas, i.e. as determined under the counterfactual (baseline) scenario (see Section 4.8.1). For example, suppose the characterisation of the current management of forest areas under the counterfactual scenario for a particular country indicated that 20% of the forest area available for wood supply was under management for wood production, whilst the remaining 80% of the area was not currently under management for wood production. Also suppose that, during a step of the iterative process, it is specified that changes need to be made to forest management, to increase wood supply, in 15% of the available forest area. The iterative process would represent these changes to management in forest areas on a pro-rata basis, i.e. in 15% of the forest area already under management for wood production, and 15% of the forest area not currently under management for wood production. In this example, this would mean that changes to forest management would involve:

- Increased extraction in 15% of the forest area already under management for production, i.e. in 15% × 20% = 3% of the available forest area

- Introduced production in 15% of the forest area previously not under management for production, i.e. in 15% × 80% = 12% of the available forest area
- No changes to forest management or wood utilisation in the remaining 85% of the available forest area (compared to the counterfactual scenario).

In considering the preceding description of the approach taken to modelling changes to forest management to increase the supply of bioenergy, it is important to recall that, as explained in Section 3.5.2, forest areas classified in National Forest Inventories as 'not available for wood production', or for management for protection, amenity or specific environmental objectives were excluded from contributing towards bioenergy supply. It should also be noted that certain assumptions applied as part of the definitions of the 'Precautionary' and 'Synergistic' approaches to forest management also placed some further constraints on, and/or adjustments to, forest areas involved in additional forest bioenergy supply (see Table 4.9 in Section 4.8.3).

From the preceding discussion, it should be apparent that the representation of changes to forest management in different countries and regions is relatively simply related to the characteristics of the forest areas under the baseline scenario. In particular, if a country or region has a relatively large area of forest identified as not currently under management for wood production, then the main changes made to forest management to increase the supply of forest bioenergy will involve introducing management for production in these areas, with a relatively small contribution made by increased extraction of biomass in areas of forest already under management for production. The converse will be true for a country or region where most forest areas are already under management for wood production. It follows that it is important to understand how the management of forest areas in different countries and regions has been characterised in this project for the counterfactual (baseline) scenario. This is particularly important because there are large regional variations. In Box 4.2, an assessment is made of the types of management practiced in forests in the main geographical regions involved in supplying forest bioenergy to the EU, as represented in the scenarios developed in this project. This assessment is derived from the patterns of forest management that were characterised in this project in developing the baseline scenarios for different countries and regions. Reference was also made to qualitative assessments of approaches to forest management in different countries and regions, as already described in the Task 1 report for this project (see in particular Section 2.4.3 and Appendix 11 of the Task 1 report).

The relatively simple approach taken in the development of assumptions about changes to forest management in different countries and regions, involved in the increased supply of forest bioenergy, has certain appeals. Essentially, changes to forest management are implemented in forest areas according to their estimated areas and their associated potentials to supply additional forest bioenergy. Such an approach also seems reasonable, in the absence of any evidence to suggest more specifically-defined changes to forest management, which might involve (for example) placing greater priority on either increased extraction or introduced production. However, it is very important to appreciate that the results of the quantitative assessment undertaken in this project are very sensitive to these assumptions. This is apparent from the discussion of the results for scenario simulations for forestry in Section 4.10, and in the outcomes of the assessment of the final project results in Section 6. It is pertinent to note that outcomes, particularly in terms of carbon impacts associated with forest bioenergy supplied to the EU from different countries and regions, could be very different to that suggested by the quantitative assessment made in this project, depending on how forest management actually changes in the future, to meet any increased demands from the EU region. Ideally, there is a case for developing and assessing further scenarios, representing different storylines for changes in forest management to supply increased levels of forest bioenergy. Unfortunately, this would involve a considerable proliferation in the number of scenarios, which was beyond the scope of this current project. Such an exercise could be a worthy subject for further research.

Box 4.2 Characteristics of current forest management (i.e. under a baseline scenario) in major regions relevant to this project

As explained in Section 4.6.1 (see in particular Table 4.3), five geographical regions were identified as of particular relevance to this project, in terms of potentially supplying forest bioenergy to the EU:

- The EU region (specifically, the EU27 region), i.e. domestic supply of forest bioenergy
- The CIS region
- Canada
- USA
- The LAM region.

EU region

Based on the characterisation of the baseline scenario for forest management in the EU27 region (see Section 4.8.1), it is estimated that about 70% of the forest area classified as available for wood supply in the EU27 region is already under management for wood production. (This may represent around 60% of the total forest area in the EU27 region; see Table 2.7, Section 2.4.3 of the Task 1 report for this project.) The percentage area in individual Member States varies significantly from this overall result for the EU27 region, perhaps by as much as between 10% and 90% (*op. cit.*).

In the EU27 region, the management of forest areas for wood production is relatively intensive, involving active silvicultural management over the life cycles of forest stands, frequently including active assistance to stand regeneration (e.g. tree planting or the retention of seed trees) and regular thinning from early on in the rotations of stands.

Box 4.2 (continued) Characteristics of current forest management (i.e. under a baseline scenario) in major regions relevant to this project

EU region (continued)

Key principles and practices of forest management have been described in Section 2.3 of the Task 1 report for this project, and these are of particular relevance to the EU region. The majority of forest stands managed for wood production in the EU are high forest stands, managed on long rotations (e.g. 80 to 150 years or more), consisting of:

- Even-aged stands, with periodic clearfelling and, typically, regular thinning over the rotation
- Even-aged stands, with regular thinning and periodic clearfelling, retaining a component of mature, seed-bearing trees to support stand regeneration
- Stands with trees of many ages with a complex structure, managed according to continuous cover silviculture.

There are also smaller areas of even-aged forest stands which are managed on a clearfell/replant/regenerate regime, on shorter rotations (e.g. 40 to 60 years), that maximise total production over the rotation (see Appendix 2 of the Task 1 report for this project). There are also some areas of fast-growing stands managed on very short rotations (e.g. 15 to 40 years), producing primarily small roundwood. These areas can be significant in some Member States.

In some EU Member States, there are areas of forests managed on relatively short rotations, or as coppice. In some cases, this current management represents a response to historical degradation or over-exploitation of what were previously high forest stands.

CIS region

It is important to note that the modelling of scenarios, as undertaken in this project, indicates that the CIS region will make a small contribution to total forest bioenergy supply to the EU region. However, for completeness, a contribution to forest bioenergy supply from the CIS region has been included in all scenarios (see Sections 4.8.2 and 4.8.3). Based on the characterisation of the baseline scenario for forest management in the CIS region (see Section 4.8.1), it is estimated that about 12% of the forest area classified as available for wood supply in the CIS region is currently under management for wood production. This result is likely to be an under-estimate, for reasons related to the definition of extensive forest management, as explained in the ensuing discussion of forest management in Canada.

Patterns of management in the CIS region are similar to those described below in this information box for Canada.

Box 4.2 (continued) Characteristics of current forest management (i.e. under a baseline scenario) in major regions relevant to this project

Canada

The forest area in Canada is very large, at just under 350 Mha (Natural Resources Canada, 2015), more than double the forest area of the EU27 region. Of this area, just over 230 Mha (65%) is classified as "managed" for the purposes of reporting GHG inventories under the UNFCCC (*op. cit.*). However, this definition is unlikely to equate to management for wood production. Based on the characterisation of the baseline scenario for forest management in Canada (see Section 4.8.1), it is estimated that less than 5% of the forest area classified as available for wood supply in Canada is currently under management for wood production. This result appears to be an under-estimate, and this reflects a rather grey distinction between areas under management for production, and not under management for production, for a large proportion of the forest area in Canada, as explained below.

In some regions of Canada, the growth rates of forest stands are very low, particularly in northern Canada, and the accessibility of forest areas is variable. These and other factors lead to significant regional variations in approaches to management. In eastern Canada and the western coastal region of Canada, forest management is generally intensive, and follows principles and practices similar to those described for the majority of forest areas in the EU27 region. In other regions of Canada, there are significant areas of forest that might be described as under extensive management, reflecting the large areas of natural/semi-natural forest in these regions, and also the relatively slow growth rates often exhibited by stands. Under extensive management, individual stands are assessed for their suitability for felling and harvesting, considering a number of economic and environmental criteria. Generally, the stands identified are mature, and selected to achieve high revenue from harvesting and production. Following felling, the forest areas may be left to regenerate naturally, or some active support to this process may be given, e.g. involving site preparation to encourage natural regeneration. Some early tending of stands may be practiced during the establishment and thicket stages (see Section 2.3 of the Task 1 report of this project). It is important to stress that, in all regions in Canada there are legislated criteria for stand re-establishment within a specified time following felling, which apply to areas under both intensive and extensive management.

Following re-establishment, forest stands under extensive management are, in effect, left to grow back to maturity with little or no intervention. An exception is fire suppression, which is practiced in all areas under management for wood production. However, sometimes decisions may be taken not to fight forest fires, for ecological reasons or due to resource constraints (particularly in years when fire outbreaks are severe). Thinning is often not practiced in forest areas under extensive management, or is limited to very early interventions to ensure good quality and development of a final stand of trees. Rotations may be very long, 100 years or much longer.

Box 4.2 (continued) Characteristics of current forest management (i.e. under a baseline scenario) in major regions relevant to this project

Canada (continued)

It should be evident from the description of forest areas under extensive management, particularly with regard to the relatively limited management interventions, and the long rotations involved, that the distinction between forest areas under active management for production, and areas not currently under active management for production, is rather grey. However, it is important to stress that in all situations, generally, key principles of sustainable forest management are adhered to, e.g., management for sustainable yield. It is important to bear this point in mind when interpreting the results simulated by the CARBINE model for Canada, for example, in terms of types of forest area involved (see Section 4.10.1) and the emphasis on production from clearfelling, with relatively low levels of thinning.

USA

Patterns of management in the USA are a combination of those described earlier in this information box for the EU27 region and for Canada. The area represented by forests under extensive management is somewhat lower in the USA, compared with Canada. Based on the characterisation of the baseline scenario for forest management in the USA (see Section 4.8.1), it is estimated that about 40% of the forest area classified as available for wood supply in the USA is currently under management for wood production. This result may be a slight under-estimate, for reasons related to the definition of extensive forest management, as explained in the preceding discussion of forest management in Canada.

LAM region

For the LAM region, forest bioenergy supply is assumed in this project to be derived from very specific sources, i.e. purpose-grown plantation forests established on abandoned and degraded agricultural land in Brazil. This option is only relevant as part of the definition of the 'Synergistic' approach to forest management and wood use (see Section 4.8.3). The approaches to the management of such plantation forests in Brazil have been discussed in Couto *et al.* (2011). Due to the specific nature of forest bioenergy sources represented in this project, further and wider consideration of approaches to forest management in Brazil and/or Latin America is not of relevance to this project. However, it may be noted that the application of existing sustainability criteria to sources of harvested wood and their associated forest areas would preclude certain types of biomass supply, e.g. where this involved deforestation

4.9. Results of scenario simulations: agriculture

4.9.1. Biomass production from annual and perennial crops

The results for the amount of bioenergy from annual and perennial crops, as simulated by the VTT-TIAM model (see Section 3 of this report), were disaggregated to the NUTS2 level and into the respective energy crops based on the BiomassFutures potential data. The bioenergy use was converted into dry matter crop production using the lower heating values for the respective crops (Figure 4.19). Rapeseed is the main biodiesel crop, whereas barley and wheat are the most important bioethanol crops. Miscanthus and switchgrass are the main grassy perennial crops, while canary reed is only present in a few countries. For the woody crops, poplar and willow have a similar share.

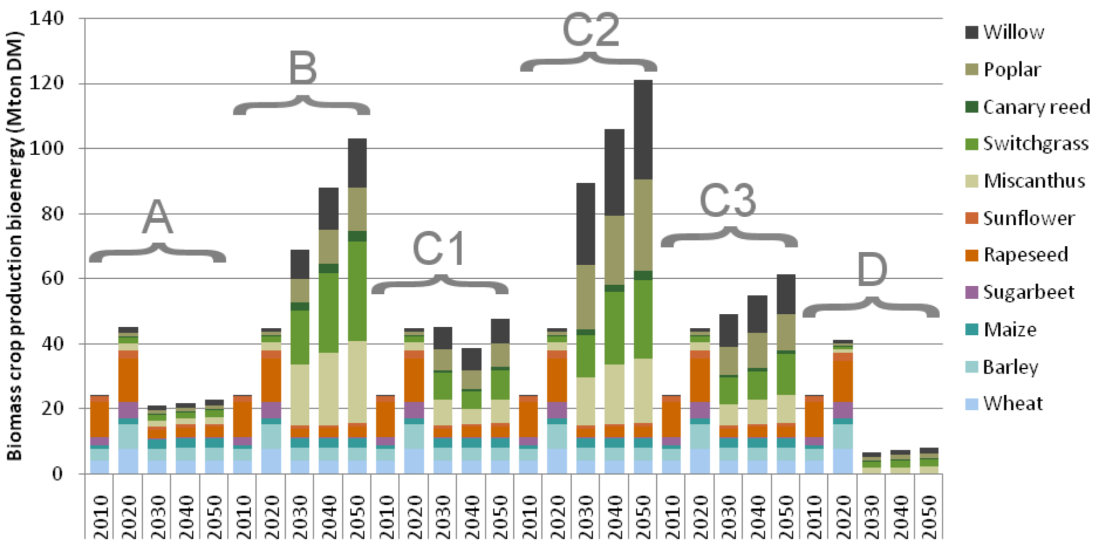

Figure 4.19. Disaggregation of the bioenergy crops for each scenario for the EU27. (Note: 1 Mton DM = 1 Modt.)

4.9.2. Areas of perennial crops

For perennial crops, the biomass production results (Figure 4.19) were converted into crop areas based on crop yields from the EEA (2013) study. For annual crops, no change in land use between scenarios was accounted for, as it was assumed that the total area of these crops would not change. Since the annual crops can be used for food, feed or bioenergy, only the share used for bioenergy (biofuels) is assumed to change. Obviously there can be impacts due to iLUC related to a shift in use of these annual crops. However, the development of the scenarios explicitly allowed for the avoidance of iLUC (see Section 3.3.3). One consequence is that the extent of annual crops decreases in all scenarios from 2020. In 2010, there were almost no perennial crops, whilst in the high-bioenergy scenarios, especially Scenario C2 (‘Carry on/domestic crops’), the area is projected to increase up to 8.4 million ha by 2050. About 60% of this area is used for woody energy crops and 40% for grassy energy crops, mainly miscanthus and switchgrass (Figure 4.20).

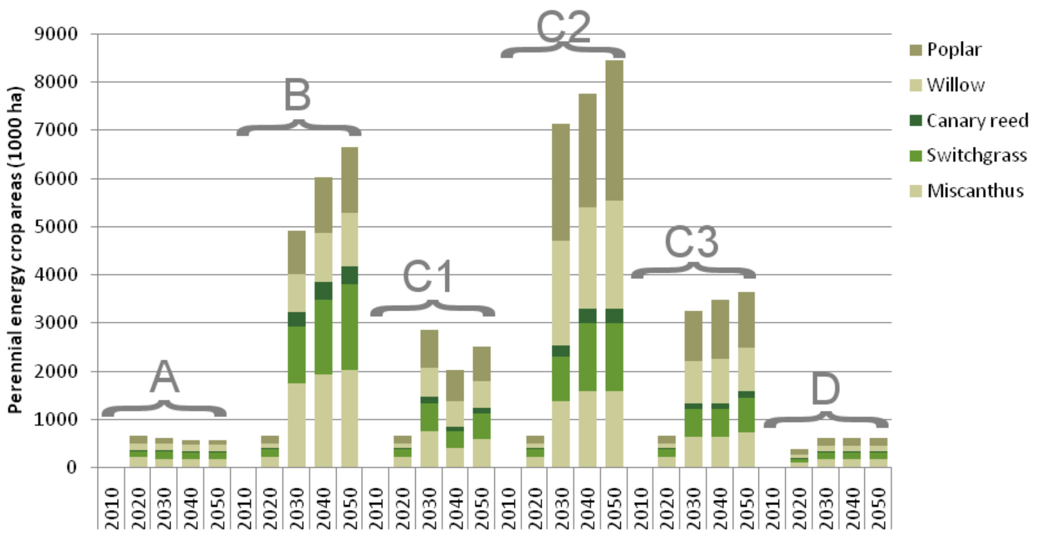

Figure 4.20. Areas of perennial energy crops in the EU27 for each scenario.

4.9.3. Contribution to bioenergy supply from straw-yielding crops

The use of straw for bioenergy, as calculated by the VTT-TIAM model for the different scenarios, was also disaggregated into the different straw crops, based on the straw potentials calculated by MITERRA-Europe (multiplication of crop area, crop yield and straw fraction). The main crops that provide straw are wheat, barley and grain maize, although the shares (i.e. relative contributions) vary by country (Figure 4.21). These shares were used to disaggregate the straw use for bioenergy for all scenarios.

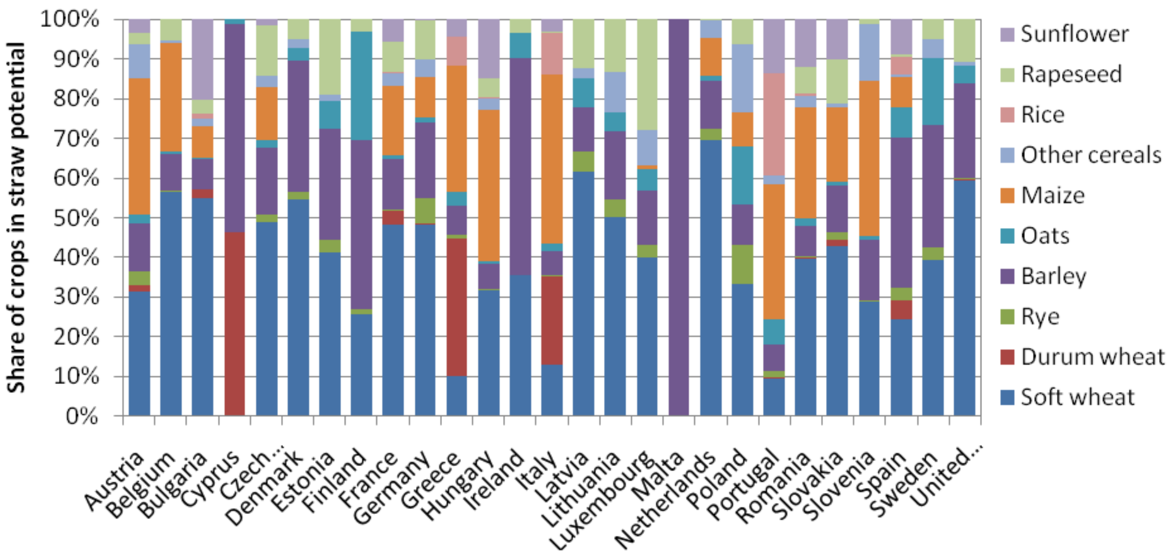

Figure 4.21. Share of (contribution made by) crops contributing to straw potential.

4.9.4. Biogenic carbon emissions

The final calculated CO_2 emissions from agricultural land for each scenario over time are shown in Figure 4.22. These emissions are the result of the aggregated SOC balance for all agricultural land uses and all NUTS2 regions. The increase in emissions in the period 2010 to 2020 of about 20 $MtCO_2$ is caused by a decrease in the grassland area and a strong increase in the set-aside/abandoned land area. This last category might also include land that is converted to settlement or forest as the total area was set equal for all years. Grassland has on average a positive SOC balance, whereas set-aside land has a negative SOC balance. For 2030 and onwards there are clear differences between the scenarios. Scenarios B ('Carry on/unconstrained use') and C2 ('Carry on/domestic crops') have the lowest emissions, since in these scenarios there is a marked increase in the area of perennial energy crops. These crops have on average a positive SOC balance, because of the permanent roots, which can increase the soil carbon content. In Scenarios A (Reference) and D ('Back off'), the area of perennial energy crops is much lower and the set-aside/abandoned land area is higher, which results in higher CO_2 emissions.

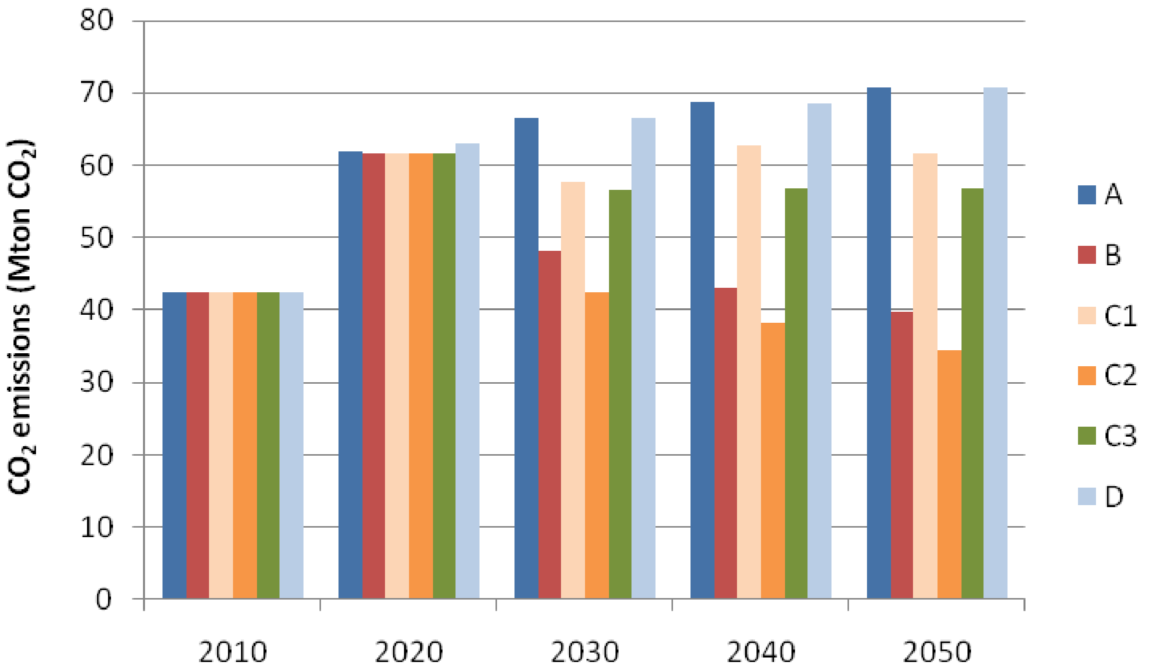

Figure 4.22. CO_2 emissions from mineral soils on agricultural land in the EU27 region for the different scenarios.

Figure 4.23 shows the CO_2 emissions related to soil carbon stock changes due to the removal of straw for bioenergy. The emissions were assessed separately from the SOC changes due to land use change, to be able to show the respective effects on the biogenic carbon emission. Only the soil carbon emissions from straw harvest for bioenergy were assessed, not the other possible uses of straw (e.g. for fodder or bedding material). The emissions were calculated relative to the year 2020 for Scenario B ('Carry on/unconstrained use'), to be able to add these emissions to the land use related emissions to derive the total biogenic carbon emissions. In 2010, the CO_2 emissions from SOC change due to straw use were negative, as there was hardly any use of straw for bioenergy compared to 2020. In the RothC calculations, it is assumed that straw is left on the field and provides a carbon input to the soil. After 2020, there is a clear scenario-dependent effect in the CO_2 emissions. Scenarios B and C2 have high emissions, as most of the potential straw is removed for bioenergy, while in the other scenarios less straw is used for bioenergy.

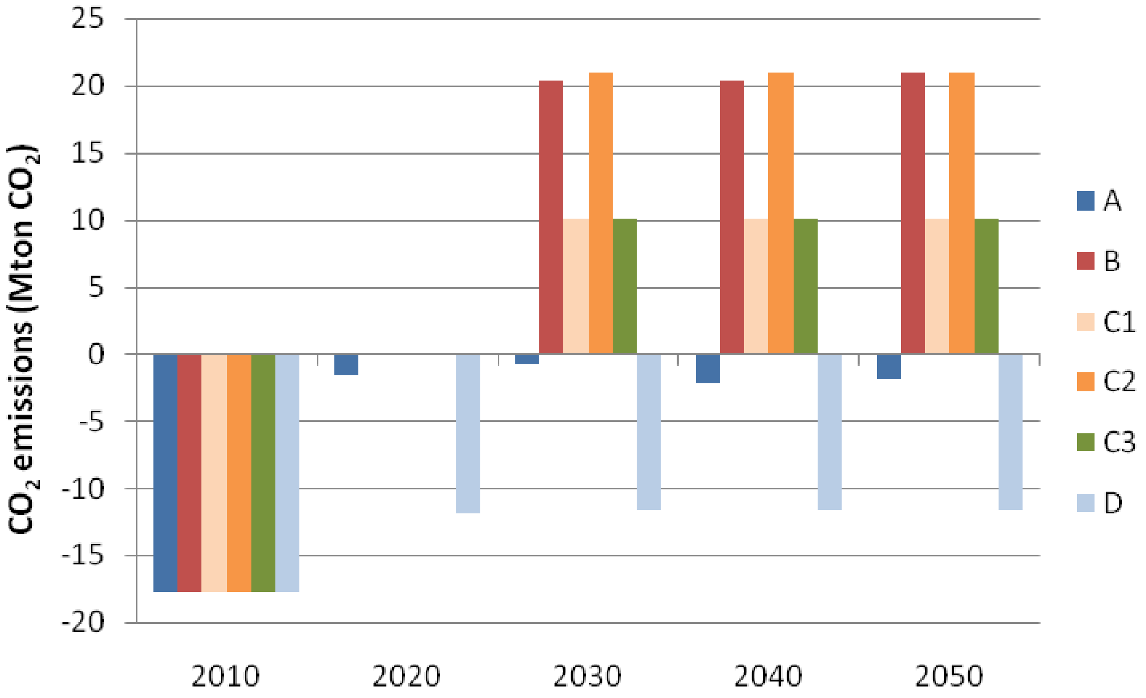

Figure 4.23. CO_2 emissions from SOC change due to straw use for bioenergy ($MtCO_2$). Emissions are positive, sequestration is negative; values are relative to 2020 in Scenario B.

Table 4.11 shows the total biogenic carbon emissions from agricultural land and straw use for bioenergy. For 2010, emissions are low because of the combined effect of low straw use for bioenergy, a smaller area of set-aside/abandoned land, and a larger area of grassland. From 2020, the scenarios diverge, with lower CO_2 emissions in Scenario D due to the lower use of straw for bioenergy. In 2030 and 2040, Scenario D still has the lowest biogenic carbon emissions, but by 2050 Scenario C2 has the lowest CO_2 emissions because of the large area of perennial energy crops. In the scenarios with high use of agricultural biomass (B and C2), the high emissions from straw removal for bioenergy, leading to negative SOC balances, are compensated by increased carbon sequestration by the perennial energy crops.

Table 4.11 Net biogenic carbon emissions from agricultural land by scenario in $MtCO_2$ (sum of Figures 4.22 and 4.23)

Year	Net biogenic carbon emissions ($MtCO_2\ yr^{-1}$)					
	A	B	C1	C2	C3	D
2010	24.7	24.7	24.7	24.7	24.7	24.7
2020	60.2	61.7	61.7	61.7	61.7	51.0
2030	65.8	68.5	67.6	63.4	66.5	54.8
2040	66.4	63.4	72.8	59.1	66.9	56.9
2050	69.0	60.7	71.7	55.4	66.8	59.0

Based on the results in Table 4.11, and the results for energy supplied by agricultural biomass, presented in Section 3.7.2, biogenic carbon emissions per unit of energy supplied in 2050 may be estimated to be roughly in the range 12 to 24 $gCO_2\ MJ^{-1}$. These values are considerably less than direct fossil-carbon emissions associated with fossil energy sources (e.g. 53 $gCO_2\ MJ^{-1}$ for natural gas, see Table 1.1 in Section 1.2 of the Task 1 report for this project).

Apart from impacts on carbon stocks and carbon sequestration (as considered in this section), the removal of agricultural crop residues for use as bioenergy will generally have impacts on the nutrient regime of affected agricultural land areas. In many situations, it will be necessary to remediate any nutrient deficiencies arising from such practice (e.g. through the application of fertiliser). The GHG emissions associated with possible remedial activities (e.g. the application of additional fertiliser) have been assessed. It should also be noted that the impact of removing crop residues on N_2O emissions (which are likely to be reduced) have also been assessed in this project.

4.10. Results of scenario simulations: forestry

As described earlier in this section, the CARBINE model was applied in this project to model the development of forests in a large number of countries which may be involved in the supply of forest bioenergy to the EU region. The CARBINE model produces a wide range of outputs describing results relevant to forests and wood production, for example:

- Areas of forest over time, classified as recently afforested, not under management for production, managed for production etc.
- Levels of wood supply over time for bioenergy and material wood products
- Development of forest carbon stocks and carbon sequestration over time
- Development of very approximate biogenic carbon emissions factors for forest bioenergy over time.

Examples of these results have been illustrated in Appendix 8, for a relatively simple case of an individual stand of trees.

The results produced by the CARBINE model for the scenarios developed in this project form a considerable body of information. A set of results of the types listed above is provided for all scenarios in Appendix 11. Examples of these results are discussed below.

4.10.1. Areas involved in forest bioenergy supply

Figures 4.24, 4.25, 4.26 and 4.27 show the projected development of forest areas over time for an example scenario, respectively, for the EU27 region, the CIS region, Canada and the USA (see Table 4.3, Section 4.6.1 for definition of regions). The example is based on the results for Scenario A ('Reference') and the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). There are no results for the LAM region (Brazil) because a contribution from this region is only represented under the 'Synergistic' approach to forest management.

Forest areas in the figures are classified according to the categories defined in Table 4.12.

Table 4.12 Definition of categories of forest area referred to in Figures 4.24 to 4.27

Category	Description
No production	This category represents areas of forest in which no active management for wood production occurs under a baseline or counterfactual scenario. However, as explained in Section 4.8.1, in principle, these areas are available for wood supply. Forest areas strictly managed as reserves or for protection are excluded. Forest areas subject to natural disturbance are also included in this category, including those areas where salvage logging takes place. However, in relative terms, these areas (and any production from salvage logging) are small. Typically, areas assigned as 'No production' can be allocated to production over time in order to meet increased requirements for forest bioenergy. When this occurs, the relevant areas are reallocated to the category 'Introduced production'. Consequently, the area represented by the category 'No production' typically decreases over time as wood production and supply is increased.
BAU production	This category represents areas of forest which are under active management for wood production under a baseline or counterfactual scenario. Under a scenario, the management of these areas may be changed to increase the production and supply of bioenergy. As explained in Section 4.8.3 (see in particular Tables 4.9 and 4.10), changed management was characterised in this project as principally involving increased extraction of harvest residues, and the prescribing of harvested 'small trees' exclusively for the production of bioenergy. When such a change of management occurs, the relevant areas are reallocated to the category 'Increased extraction'. The area represented by the category 'BAU production' typically decreases over time as wood production and supply is increased. This is because the areas are no longer subject to the management prescribed under a baseline or counterfactual scenario.

Table 4.12 (continued) Definition of categories of forest area referred to in Figures 4.24 to 4.27

Category	Description
Introduced production	This category represents forest areas previously not under management for wood production, in which management for wood production is introduced as part of a scenario, in order to meet increased requirements for forest bioenergy. Typically this involves harvesting trees through thinning and felling, with some co-production of material wood products, as defined for the 'Precautionary' and 'Synergistic' approaches (see Section 4.8.3). It is important to note that, when an area of forest is assigned to this category, management for wood production may not start immediately and may not start for some decades. This is because the CARBINE model allocates sufficient forest area for production to permit smooth supply of forest bioenergy to meet the target levels in the scenarios over time.
Increased extraction	This category represents forest areas which were already under management for production, in which management is changed to increase the production and supply of forest bioenergy. As explained in Section 4.8.3 (see in particular Tables 4.9 and 4.10), changed management was characterised in this project as principally involving increased extraction of harvest residues, and the prescribing of harvested 'small trees' exclusively for the production of bioenergy. It is important to note that, when an area of forest is assigned to this category, changed management for bioenergy production may not start immediately and may not start for some decades. This is because the CARBINE model allocates sufficient forest area to changed management for increased extraction to permit smooth supply of forest bioenergy to meet the target levels in the scenarios over time.
Afforestation	This category represents areas afforested since the beginning of the period represented in the figures in this section, i.e. 2005. Under the 'Precautionary' approach to forest management, afforested areas contribute initially as a supplement to the areas categorised as 'No production' and 'BAU production'. Subsequently, afforestation may contribute towards the areas categorised as 'Introduced production' and 'Increased extraction'. Under the 'Synergistic' approach, from 2016 onwards, all afforested areas are assumed to contribute either to 'BAU production' or 'Increased extraction' (see Sections 4.7.2 and 4.8.3).

Note that the scale on the y-axis of Figure 4.26 is double the scale of the other figures, because the total area of forest in Canada is much greater than for the other regions considered in this project.

Considering first the impacts on forest areas in the CIS region (Figure 4.25), the areas involved in supplying forest bioenergy to the EU region under Reference Scenario A are relatively small, at less than 10% of the forest areas in the CIS identified as available for wood supply. However, this reflects the relatively small quantities of forest bioenergy projected as supplied to the EU from the CIS. In this context, the forest areas involved may appear to be quite large. However, the forest areas reported by the CARBINE model according to the categories in Table 4.12, also include areas where management is changed to ensure that 2005 levels of forest bioenergy consumed domestically in the CIS region continue to be met. As a consequence, the forest areas involved in changes to meet increased forest bioenergy supply to the EU region are over-estimated to some extent in Figure 4.25. Due to the details of tracking of forest areas in the CARBINE model, it was not possible to further disaggregate forest areas. The preceding assessment of forest areas in the CIS region applies for all scenarios because the assumptions made for the CIS did not vary with scenario, due to the relatively small quantities of forest bioenergy involved.

In the case of Canada and the USA (Figures 4.26 and 4.27), the forest areas involved in supplying forest bioenergy to the EU region are also relatively small. This is particularly apparent for Canada, reflecting the relatively very large total area of forests.

For all regions external to the EU, the increased supply of forest bioenergy to the EU region is simulated to involve a significant contribution due to the introduction of management for production in areas where currently this is not taking place. This is a reflection of the modelling approach in this project, which allocates areas for the supply of forest bioenergy according to their potentials, as described in Sections 4.8.3 and 4.8.4. In the case of the CIS region, Canada and the USA, the areas of forest not under active management for production, but categorised as available for wood supply are significant, although the definition of areas not currently under active management for production is rather grey, for reasons explained in Box 4.2, Section 4.8.4.

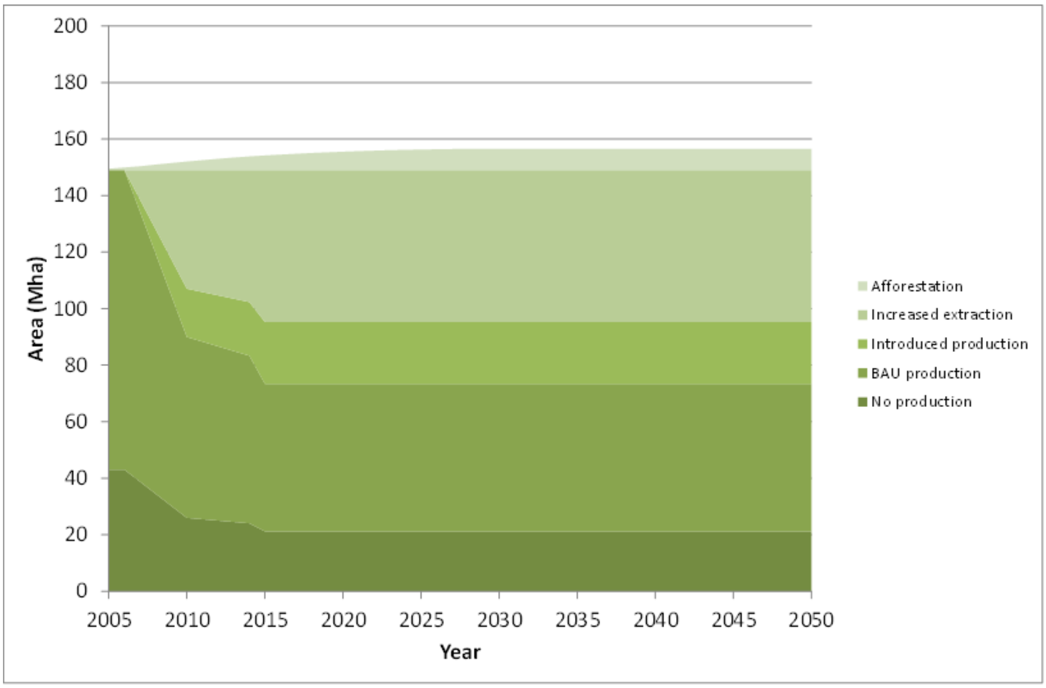

Figure 4.24. Development of forest areas over time in the EU27 region under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

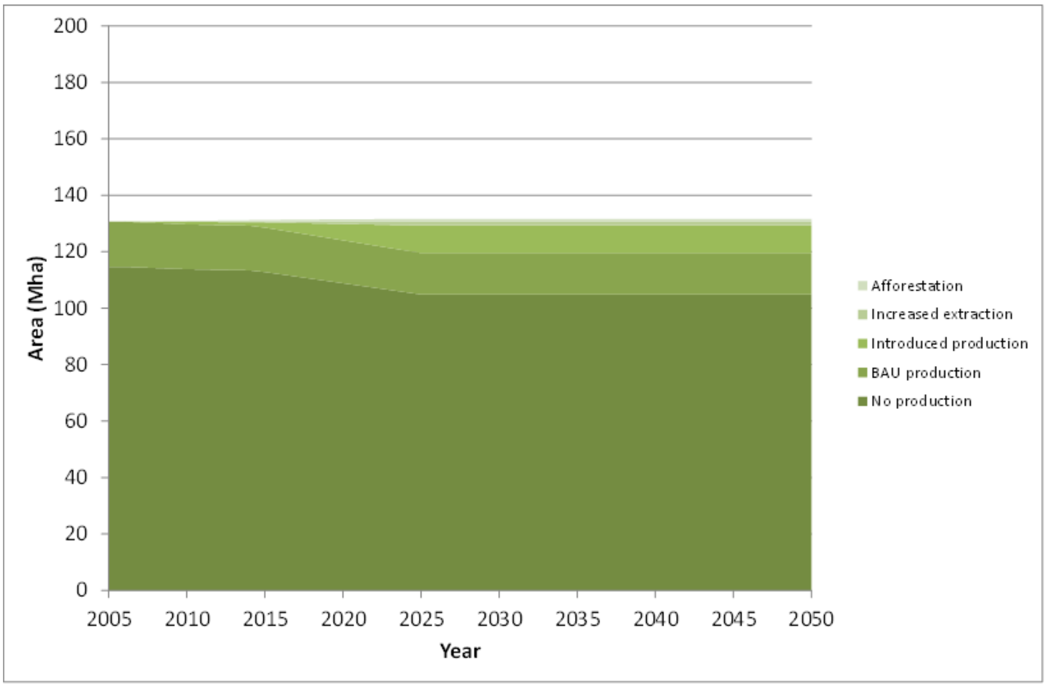

Figure 4.25. Development of forest areas over time in the CIS region under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

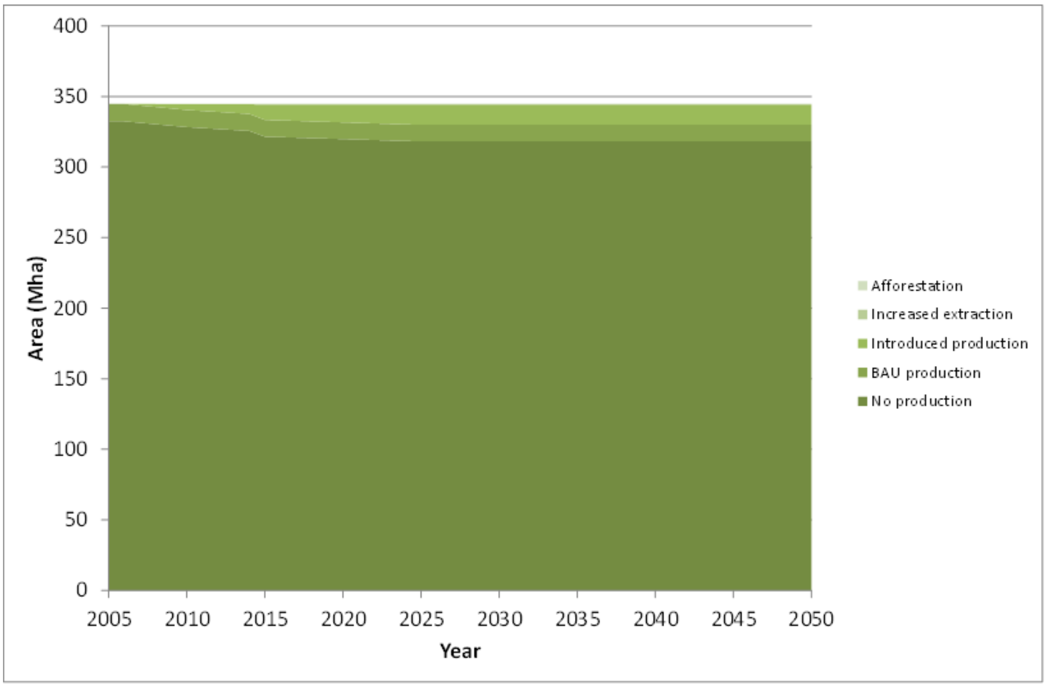

Figure 4.26. Development of forest areas over time in Canada under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

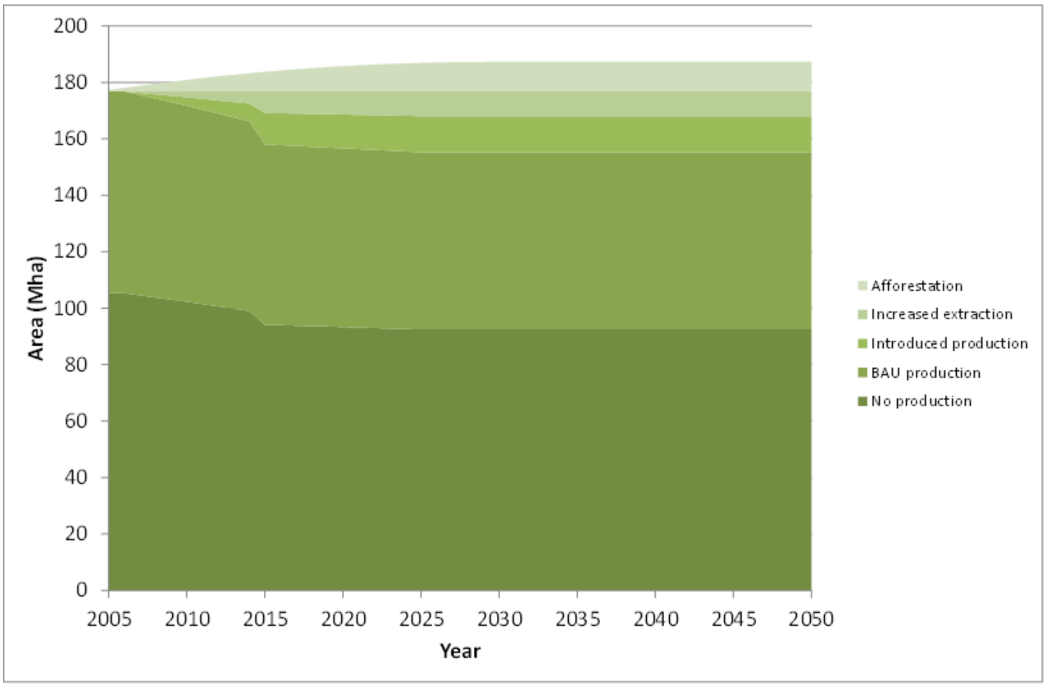

Figure 4.27. Development of forest areas over time in the USA under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

The biggest changes in the management of forest areas are projected to take place in the EU27 region (Figure 4.24). Roughly half the area initially categorised as not managed for production is projected to be brought into production, whilst increased extraction of wood for bioenergy is projected to take place in about half the area already under management for production. This reflects the fact that, for the Reference Scenario A, domestic supply of forest bioenergy makes a big contribution to the total requirement in the EU region, compared with supplies imported from other regions. For the EU27 region, the increased extraction of wood for bioenergy in forest areas already under management for production is projected to make a much more important contribution to forest bioenergy supply, compared to the results for imported wood. This reflects the fact that a proportionally greater area of forests in the EU is already under management for production compared with importing regions (see Box 4.2 in Section 4.8.4).

The results in Figures 4.24 to 4.27 are all based on Reference Scenario A, in which existing 2020 targets for bioenergy consumption are met, but more ambitious targets are not set post-2020. Reflecting this, nearly all the area change in the figures is projected to take place up to 2020, with limited changes after 2020. However, for reasons explained in the descriptions in Table 4.12, actual changes to management may take place over many years subsequent to the reallocation of areas, as part of the smooth and sustained supply of required levels of forest bioenergy. It follows that changes to forest management, and consequent development of carbon stocks and carbon sequestration, take place over many decades beyond 2020.

Appendix 11 contains a set of results such as illustrated in Figures 4.24 to 4.27, covering all scenarios, all supplying regions and the 'Precautionary' and 'Synergistic' approaches to forest management and wood use to supply increased quantities of forest bioenergy.

4.10.2. Bioenergy supply from forests

Figures 4.28 and 4.29 show two examples of the projected supply of forest bioenergy over time to the EU region, respectively for domestic production in the EU27 region and for wood imported from Canada. The examples are based on results for Scenario A ('Reference') and the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). Note that the scales on the y-axes of the two figures are different. The simulated forest bioenergy supply is broken down into the woody biomass categories of:

- Harvest residues (abbreviated to 'Residues' in the figures)
- Small roundwood (abbreviated to 'Roundwood' in the figures)
- Sawmill co-products (abbreviated to 'Co-products' in the figures)
- Bark.

Definitions for these types of wood are given in Glossary for this report.

The results are in units of Mtoe and are displayed cumulatively with respect to the categories of wood, i.e. the results for small roundwood include the contributions due to harvest residues, the results for sawmill co-products include the contributions due to harvest residues and small roundwood, whilst the results for bark include the contributions due to the other three categories. The results displayed for bark thus also represent the projected total supply of forest bioenergy over time.

The figures also display overall results for impacts of forest bioenergy production on marginal production of material wood products from EU27 forests (abbreviated to 'Materials' in the figures). The impacts of increased production of forest bioenergy on the marginal supply of material wood products can be both positive (arising from co-production of materials alongside forest bioenergy) and negative (due to competition for the available wood resource for use either as forest bioenergy or for material wood products). The results for the supply of material wood products are expressed in units of Mtoe for compatibility with the results for forest bioenergy, and are also displayed cumulatively with respect to forest bioenergy supply. Since the impacts of forest bioenergy supply on the supply of material wood products can be positive, negative or indeed neutral, the trajectories in the figures representing the marginal supply of material wood products can be located above, below or coincident with the trajectories for total forest bioenergy supply.

In the case of example results for domestic supply from within the EU27 region, Figure 4.28 shows how the CARBINE model has simulated the total supply of forest bioenergy to smoothly match the decadal target levels for forest bioenergy consumption between 2010 to 2050, as determined by the VTT-TIAM model, as part of the analysis of scenarios in Task 2 (see Section 3 and Section 4.8.2). The target levels of forest bioenergy supply are shown in Figure 4.28 (and Figure 4.29) as orange diamonds; the precise match of simulated forest bioenergy supply is evident.

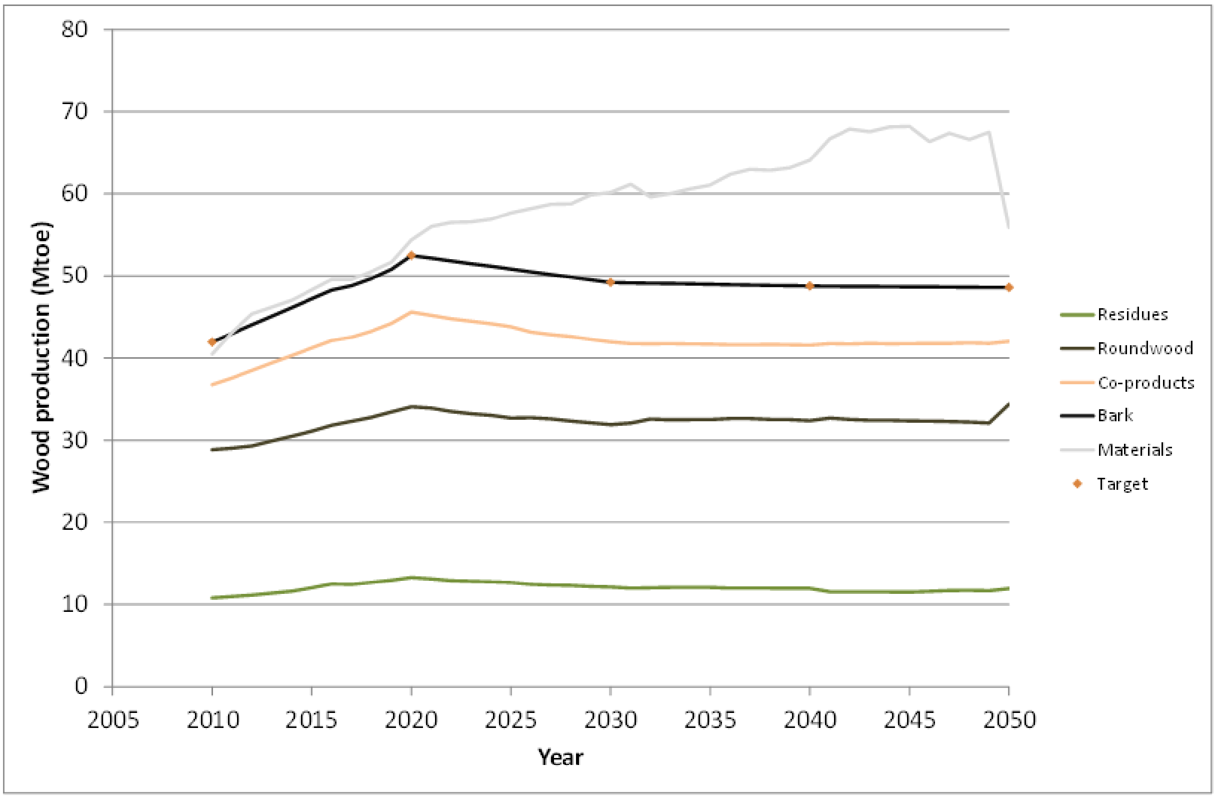

Figure 4.28. Projected supply of forest bioenergy and marginal total supply of material wood products over time from forests in the EU27 region under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

The results in Figure 4.28 also show that the main contributions to total supply of forest bioenergy from the EU27 region are due to small roundwood (in large part in the form of small trees), followed by harvest residues. Contributions from sawmill co-products and bark are smaller but significant. This result reflects the fact that the major contribution to the supply of forest bioenergy from within the EU27 region is projected to involve increased extraction of wood for forest bioenergy from forest areas already under management for production (see Section 4.8.4).

Over the period 2010 to 2020, the overall marginal impact of increased forest bioenergy production on supplies of material wood products is neutral. This is apparent from Figure 4.28, in that the trajectory for 'Materials' is almost coincident over this period with the trajectory for 'Bark' (i.e. total forest bioenergy supply). However, as discussed later in this section, this overall result disguises more detailed shifts in the supply of particular categories of material wood products. After 2020, the marginal impact of increased forest bioenergy production on supply of material wood products from EU27 forests is projected to be increasingly positive overall. This reflects the consequence of mobilising forest resources in the EU27 region to meet additional requirements for forest bioenergy, i.e. there will inevitably be an element of complementary production of wood for use as materials.

In the case of example results for supply of forest bioenergy from Canada to the EU region, Figure 4.29 shows how the CARBINE model has simulated the total supply of forest bioenergy and marginal impacts on the total supply of material wood products.

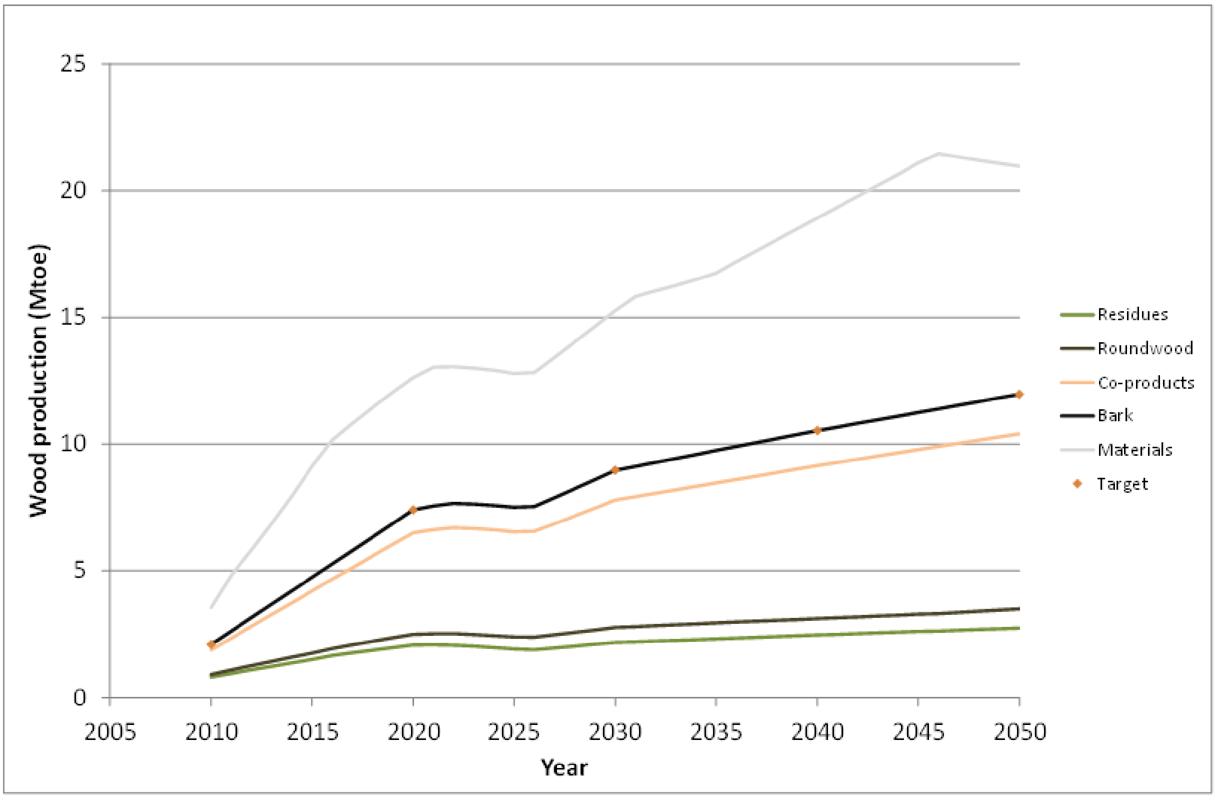

Figure 4.29. Projected supply of forest bioenergy to the EU region and marginal total supply of material wood products over time from forests in Canada under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

For supplies of forest bioenergy to the EU region from Canada, the results in Figure 4.29 show that the main contributions to total supply are due to sawmill co-products and, to some extent, harvest residues. Contributions from small roundwood and bark are smaller. This result reflects the fact that the major contribution to the supply of forest bioenergy from Canada to the EU27 region is projected to involve introducing additional management for production in forest areas not currently under management for production (see Section 4.8.4). In particular, because of the types of forest areas involved in the introduction of management for production, levels of harvested small roundwood (including as small trees) are projected to be relatively low.

The overall marginal impact of increased forest bioenergy production in Canada on supplies of material wood products is projected to be quite positive. This is apparent from Figure 4.29, in that the trajectory for 'Materials' is significantly above with the trajectory for 'Bark' (i.e. total forest bioenergy supply). This reflects the consequence of mobilising forest resources in Canada to meet additional requirements for forest bioenergy in the EU region, i.e. there will inevitably be an element of complementary production of wood for use as materials, particularly in cases where management for production is introduced in forest areas not currently under management for production. As part of the approach to modelling forestry and carbon impacts in this project, there is no presumption that the additional supply of material wood products from forests in regions outside the EU will also be consumed within the EU region, i.e. it may be consumed in any region and perhaps domestically within the supplier region. It may be noted that the marginal increase in total supply of materials from forests in Canada by 2050, associated with increased supply of forest bioenergy to the EU region, represents an increase of less than 20% in the level of production of industrial roundwood reported for Canada for the year 2005, as reported in FAO statistics (see Table 4.6, Section 4.8.1).

It is apparent from a comparison of Figures 4.28 and 4.29 that, for the Reference Scenario A, the major contribution to supplies of forest bioenergy in the EU region is due to domestic production from EU27 forests. However, an important distinction must be made between the results for the EU27 in Figure 4.28 and the results for Canada in Figure 4.29. The results for the EU27 in Figure 4.28 represent absolute quantities of forest bioenergy consumed and supplied in the EU region. (A simplifying assumption was made that all forest bioenergy produced in the EU would also be consumed in the EU.) Because the results are for absolute quantities, they represent the supply of forest bioenergy to meet existing demand (i.e. under business as usual) as well as additional demand implied by a scenario. In contrast, the results for Canada in Figure 4.29 represent marginal quantities of forest bioenergy, i.e. specifically the additional supply of forest bioenergy to meet the demand from the EU region. Hence, the results for Canada do not include forest bioenergy supplied for domestic consumption in Canada or for consumption in other regions outside the EU. The difference in the presentation of results for the EU and for Canada is apparent in Figures 4.28 and 4.29, in that the level of forest bioenergy supply from EU27 forests in Figure 4.28 is already significant in 2010, whereas for Canada (Figure 4.29), the level of supply in 2010 is quite small.

Figure 4.30 shows the contribution made by business-as-usual production in EU27 forests to the supply of forest bioenergy within the EU region. Note that, by definition, the business-as-usual contribution to forest bioenergy supply does not vary with scenario. This figure shows that business-as-usual production in EU27 forests contributes slightly more than half of the required demand for forest bioenergy under Reference Scenario A over the period 2010 to 2050, with a slight dip in the contribution occurring around 2020, as a result of a marked increase in demand from 2010 to 2020, to meet existing EU bioenergy targets. The business-as-usual contribution to forest bioenergy supply will be relatively smaller for the higher biomass 'Carry on' Scenarios (Scenarios B, C1, C2 and C3), particularly in later years.

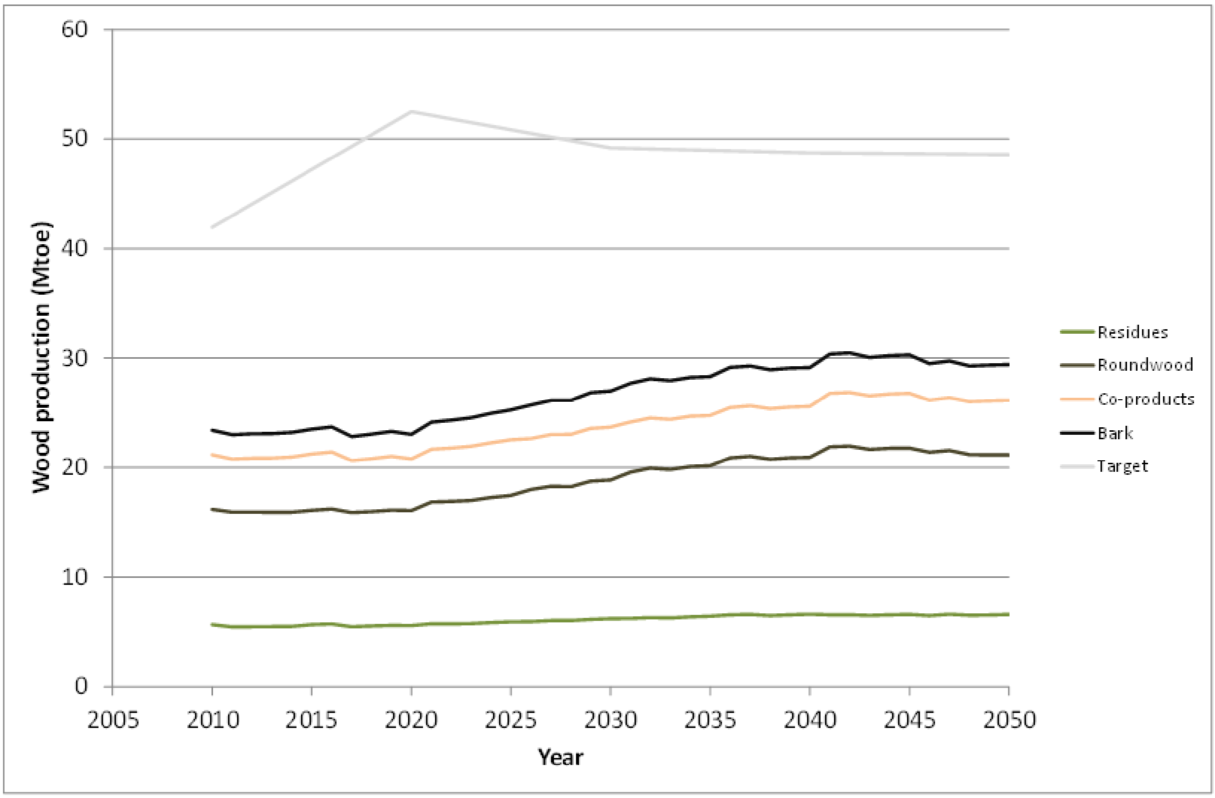

Figure 4.30. Projected supply of forest bioenergy over time from business as usual production from forests in the EU27 region.

Appendix 11 contains a set of results such as illustrated in Figures 4.28 to 4.29, covering all scenarios, all supplying regions and the 'Precautionary' and 'Synergistic' approaches to forest management and wood use to supply increased quantities of forest bioenergy.

4.10.3. Impacts on supply of wood for material products

Figure 4.31 shows an example of the projected marginal impacts on the supply of material wood products from forests in the EU27 region, as a consequence of changes in forestry practice and patterns of wood use in response to increased requirements for forest bioenergy. The example is based on results for Scenario A ('Reference') and the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). The simulated marginal supply is broken down into the categories of finished material wood products of woody biomass categories of:

- Paper
- Three categories of wood-based panels, medium density fibreboard (MDF), chipboard and oriented strand board (OSB)
- Pallets (may also include some wood used for packaging)
- Fencing (may also include some wood used for joinery)
- Structural timber
- Bark.

The results are in units of Modt and are displayed individually with respect to the categories of wood product, i.e. not cumulatively, as was the case in Figures 4.28 to 4.30.

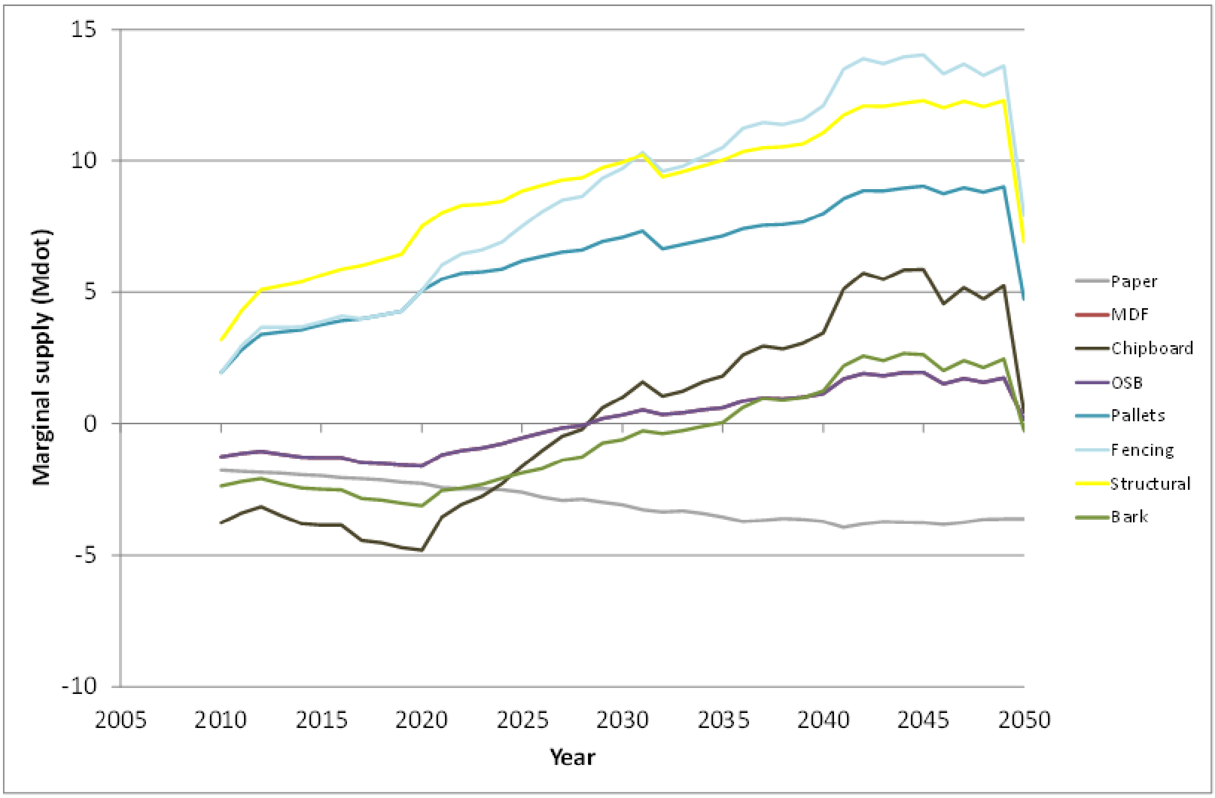

Figure 4.31. Projected marginal impacts over time on the supply of material wood products from forests in the EU27 region under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use.

The results in Figure 4.31 show that the marginal impacts on different categories of material wood product are variable. Over the period of 2010 to 2030, supplies of wood for use as paper, bark and for wood-based panels are somewhat reduced (i.e. compared to the counterfactual scenario). In contrast, supplies of wood for use as solid-wood products, such as structural timber, fencing and joinery, as pallets and as part of packaging, are all increased. These results reflect assumptions made in the modelling of forest scenarios through application of the CARBINE model. Specifically, on the one hand, changes assumed in forest management (notably prescribing small trees for use as bioenergy) and patterns of wood use (e.g. involving utilisation of some small roundwood and sawmill co-products for bioenergy) tend to divert lower grade wood sources for use as bioenergy. On the other hand, additional harvesting in forest areas to produce more forest bioenergy also involves co-production of higher grade wood sources.

From 2030 onwards, the mobilisation of the wood resource in the EU27 region, in response to the increased demand for forest bioenergy, leads to a general increase (compared to the counterfactual scenario) in the supply of wood for all material uses with the exception of paper.

Appendix 11 contains a set of results such as illustrated in Figure 4.31, covering all scenarios, all supplying regions and the 'Precautionary' and 'Synergistic' approaches to forest management and wood use to supply increased quantities of forest bioenergy.

4.10.4. Long-term sustainable-yield potential of wood supply

As described earlier in this section, as part of the modelling in Task 3, projections were made of future levels of forest bioenergy supply, as determined for a set of scenarios, and also the associated levels of supply of material wood products, up to 2050. An assessment was made to investigate whether the levels of wood supply indicated by the projections under the various scenarios were consistent with estimates of the long-term sustainable-yield potential of wood production from forest areas.

Essentially, the investigation consisted of an analysis of whether the levels of wood supply suggested in the scenarios were consistent with a fundamental principle referred to in forestry as 'sustainable yield'. A clear understanding of this principle, and the scope of a sustainable-yield analysis, is important for understanding and interpreting the results presented below. A sustainable-yield analysis is not a comprehensive assessment of the sustainability of forest management or of wood production, considering all possible criteria and impacts. Such a comprehensive assessment would consider impacts on (for example), the stability of forest sites (e.g. with respect to wind risk), the nutrient and water balances of sites, the eutrophication of surrounding watercourses and lakes, the biodiversity of forest stands and the surrounding landscape, and economic and social factors. Rather, a sustainable-yield analysis is concerned with a narrow, but crucial, assessment of whether levels of wood production from forest areas are actually achievable, given the estimated potential productivity of the forests. This assessment is usually made from a long-term perspective (i.e. over several rotations and longer timescales). Ideally, a more comprehensive assessment of the sustainability of specified levels of forest bioenergy supply is desirable. However, as a minimum fundamental requirement, scenarios for forest bioenergy supply (or wood supply more generally) need to be consistent with the principle of sustainable yield as defined here.

As a first step in the assessment, for each country forming each region considered in this project (see Table 4.3, Section 4.6.1), estimates were derived of the maximum long-term potential for wood production from forest areas. These estimates were calculated by combining forest areas reported in National Forest Inventories with their associated tree species and assumptions about growth rates. Relevant datasets had already compiled for use as input data as part of the modelling of forest areas based on the CARBINE model (see Section 4.8.1 and Appendix 9). Maximum potential standing stemwood production was first estimated in units of millions of cubic metres, by multiplying each forest area (expressed in millions of hectares) by the associated estimate of growth rate. These results were converted to units of biomass, expressed in millions of oven-dry tonnes, by multiplying the stem volumes by an assumed average wood density. A density of 0.4 odt m^{-3} was assumed for coniferous species whilst a density of 0.5 odt m^{-3} was assumed for broadleaved species. The estimates of standing stem biomass were converted to potential stem biomass production by assuming an efficiency of 90%. Potential production of branchwood biomass (additional to stemwood) was estimated by multiplying the estimates for stemwood biomass by 20%. Maximum potential biomass production from harvest residues was estimated as 10% of stemwood biomass not harvested as roundwood (i.e. due to the 90% efficiency of harvesting) plus the branchwood biomass. In this way, two estimates were derived for maximum potential biomass production from forest areas:

1 Potential biomass production from stemwood

2 Potential biomass production from harvest residues (including branchwood).

It is important to stress that these estimates of potential biomass production represent theoretical maximum productivities. In practice, such maximum productivities would rarely be achieved. This is because forest areas are typically managed for multiple objectives (see Section 2 of the Task 1 report for this project, Matthews *et al*., 2014a), which will often involve sub-optimal management, if judged in simplistic terms of raw biomass production. Furthermore, there will be significant practical and environmental constraints on the extraction of harvest residues.

In the final step of the assessment, the estimates of maximum potential biomass production were compared with estimates of the actual production of industrial roundwood and wood fuel, as reported for the year 2005 in FAO statistics (see Table 4.6, Section 4.8.1). The FAO statistics were converted from units of volume to units of biomass by multiplying by an assumed average wood density of 0.45 odt m^{-3}. In addition, projected estimates of industrial roundwood and wood fuel production were derived for each scenario for the years 2030 and 2050, by combining the results from the CARBINE model (as illustrated in Figures 4.28 and 4.29) with the FAO statistics for 2005, where relevant.

Figure 4.32 shows a comparison of estimated potential biomass production from forests in the EU27 region with actual biomass production in 2005 and projected biomass production in 2030 and 2050, for the scenarios developed in this project. The results are based on the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). As described above, the estimated potential biomass production (which does not vary with year because it represents a long-term estimate) is broken down into the categories of stemwood and harvest residues. The estimate of biomass production reported for the year 2005 is broken down into the categories of industrial roundwood and wood fuel. This reported estimate for 2005 is repeated for each set of results for each scenario. The projected estimates of biomass production under each scenario for the years 2030 and 2050 are also broken down into the categories of industrial roundwood and wood fuel.

The categorisations used for potential production and for reported and projected production are different but, in general, for levels of production to be consistent with the principle of sustainable yield:

- Reported and projected industrial roundwood production needs to be less than the maximum potential stemwood production, ideally, significantly less
- Reported and projected wood fuel production plus industrial roundwood production needs to be less than the potential production from harvest residues plus stemwood, ideally, significantly less.

For the purposes of this assessment, a threshold for sustainable-yield production of industrial roundwood and wood fuel combined has been defined as 70% of the theoretical maximum potential production of stemwood and harvest residues combined.

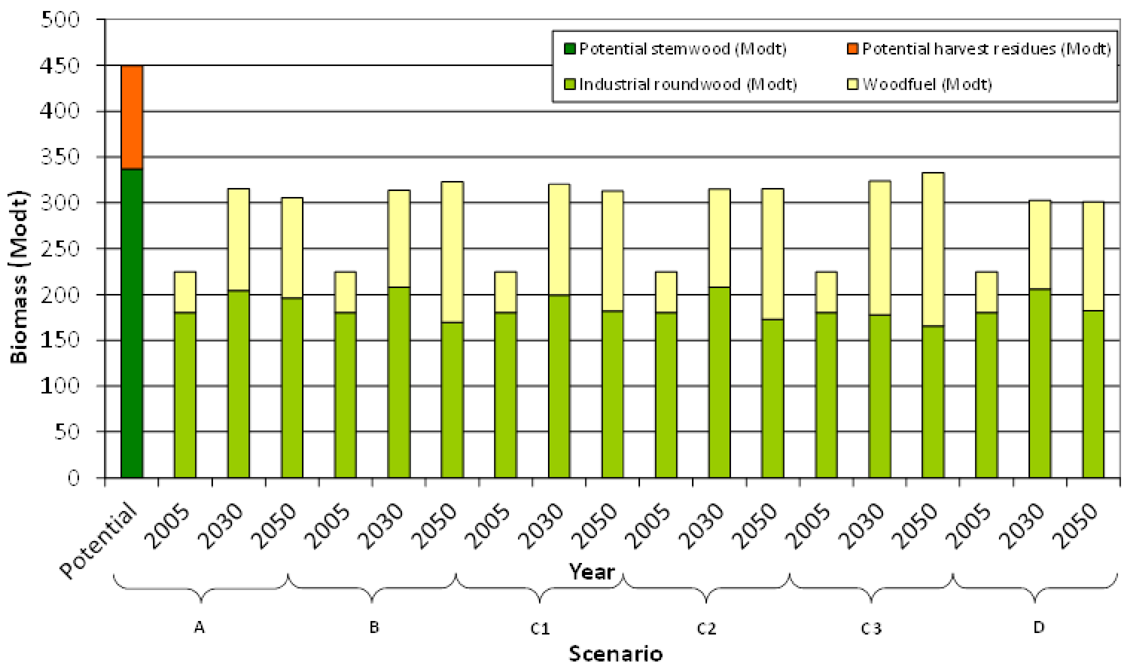

Figure 4.32. Comparison of reported and projected estimates of biomass production from EU27 forests with estimates of theoretical maximum potential production, for all scenarios, based on the 'Precautionary' approach to forest management and patterns of wood use.

Based on the assessment in Figure 4.32, the long-term theoretical maximum potential for production of biomass from EU27 forests is estimated at 449 Modt yr^{-1}, consisting of 337 Modt yr^{-1} contributed stemwood, and 112 Modt yr^{-1} contributed by harvest residues. This gives a threshold for potential sustainable-yield production of 70% of 449 Modt yr^{-1}, i.e. 314 Modt yr^{-1}.

From Figure 4.32, it is evident that reported production for 2005 is well within the estimated potential sustainable-yield threshold, even if only potential production from stemwood is considered. Production reported in 2005 for wood fuel (i.e. forest bioenergy) is small compared with the reported production of industrial roundwood. However, the share of biomass production used for forest bioenergy, relative to the production of industrial roundwood, increases significantly for all scenarios in projections for the years 2030 and 2050. Projected production of industrial roundwood in 2030 is estimated at around 200 Modt yr^{-1} for all scenarios. Projected production of forest bioenergy in 2030 varies with scenario, between 105 and 146 Modt yr^{-1}. Hence, projected total forest biomass production in 2030 is between 305 and 346 Modt yr^{-1}, depending on the scenario considered. These projected estimates approach or slightly exceed threshold specified for potential sustainable-yield production of biomass from stemwood and harvest residues in EU27 forests. If 70% is accepted as a threshold for long-term sustainable-yield potential production, then the results in Figure 4.32 suggest that projected total biomass production has approached this limit in 2030. The results in Figure 4.32 also emphasise the critical importance of a contribution from harvest residues to forest bioenergy supply from EU forests for insuring that total production of industrial roundwood and forest bioenergy is within the sustainable-yield potential. Further increases in total production above this level are likely to involve very significant risks to achieving wood supply in the EU27 region consistently with the principle of sustainable yield.

Projected total biomass production is fairly stable over the period from 2030 to 2050. Since forest bioenergy production is projected to increase significantly over this period, this suggests that the increases in forest bioenergy production displace wood supply for material wood products. Such displacement appears to be occurring in the results in Figure 4.32. These results suggest the potential for risks of competition between the energy sector and the wood products sector for the available wood resource in the EU27 region, if production of forest bioenergy were to increase significantly beyond the levels projected for 2030. Alternatively, if the production of material wood products were also to increase beyond the projected levels in 2030, very significant pressure would be placed on EU forests.

In considering the preceding assessment based on Figure 4.32, it should be noted that in estimating potential production from forests in the EU27 region, forest areas classified in National Forest Inventories as ‘not available for wood production’, or for management for protection, amenity or specific environmental objectives were excluded.

The assessment of the potential situation in the EU27 region based on Figure 4.32 is reinforced by the results based on the 'Synergistic' approach, as shown in Figure 4.33.

The results in Figure 4.33 for potential production, and for reported production in 2005, are identical to the equivalent results in Figure 4.32. The results for projected production of forest bioenergy in 2030 and 2050 for each scenario are also exactly the same as for the 'Precautionary' approach, as shown in Figure 4.32. This is because the approach to modelling forest bioenergy supply has explicitly aimed to match specified target levels for each decade from 2010 to 2050, as determined in Task 2 by the VTT-TIAM model. The substantive differences in the results for the 'Synergistic' approach are in the projected estimates for production of industrial roundwood in 2030 and particularly in 2050 for each scenario. As explained in Section 4.8.3, in comparison with the 'Precautionary' approach to wood use, the 'Synergistic' approach places greater emphasis on the co-production of material wood products alongside the increased production of forest bioenergy. The results in Figure 4.33 thus follow naturally from the assumptions made about patterns of wood use in defining the 'Synergistic' approach. Of particular note, projected levels of the production of industrial roundwood in 2050 are typically around 90% of the estimated potential stemwood production. Furthermore, levels of projected total production of industrial roundwood and forest bioenergy in 2050 also approach 90% of the estimated potential for total production. As already observed in the assessment of the results in Figure 4.32, such levels of production are likely to involve very significant risks to the sustainable-yield supply of wood from within the EU27 region.

Three important qualifications need to be attached to the preceding assessments of potential and projected wood production from forests in the EU27 region.

Firstly, as discussion of the Task 2 forest bioenergy scenarios in Section 4.8.2 highlighted, a pronounced increase in the levels of total forest bioenergy supply from some point after 2030 up to 2050 is a notable feature of the results for all the 'Carry on' Scenarios. It was noted that this feature of the Task 2 results has quite important implications for forest management and patterns of wood use to deliver the suggested increases in levels of forest bioenergy supply. The issue was considered so significant that, as part of the modelling in Task 3, adjustments were made to the original Task 2 results, to reduce the contribution from the EU27 region to forest bioenergy supply between 2040 and 2050, allocating this supply instead to imports. The assessments in Figures 4.32 and 4.33 underpin the rationale for these adjustments to the original Task 2 results. However, even the adjusted levels for supply of forest bioenergy from EU27 forests would appear to be technically and logistically challenging, and involve very significant risks to sustainable-yield production. It was also observed that the adjustments made to the original Task 2 results also had the effect of further emphasising the pronounced increase in supply of forest bioenergy from regions outside the EU in the period 2030 or 2040 (depending on the scenario) to 2050.

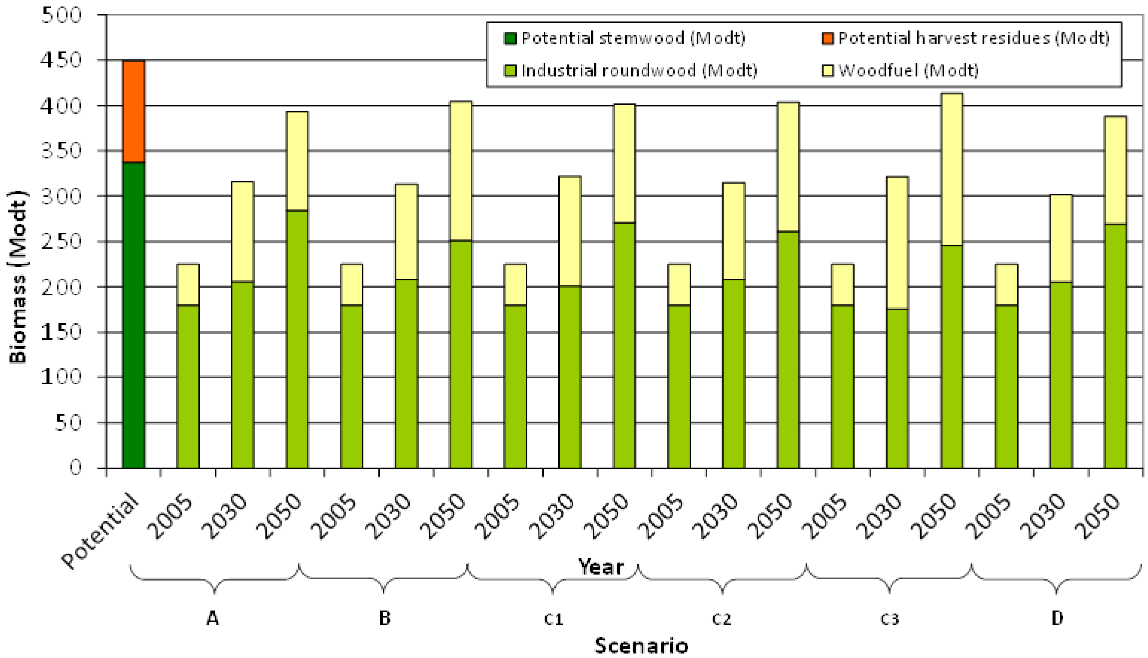

Figure 4.33. Comparison of reported and projected estimates of biomass production from EU27 forests with estimates of theoretical maximum potential production, for all scenarios, based on the 'Synergistic' approach to forest management and patterns of wood use.

Secondly, the assessment of the results in Figures 4.32 and 4.33 would appear to have significant implications for the setting of target levels for forest bioenergy consumption post-2020, should such targets be set. This point is considered further as part of the discussion of the potential to define a refined scenario for bioenergy consumption in the EU (see Section 6.11).

Thirdly, it is important to note that the estimates of potential wood production from forests in the EU27 region were based on National Forest Inventory data that, typically, represented forest areas for a base year of 2000 (see Appendix 9). It follows that no allowance has been made in these estimates for potential production from areas afforested since (roughly) the year 2000. The projected areas of afforestation in the EU27 region are small relative to the existing forest area (see Figure 4.24). However, allowance for potential production from afforested areas would discount to some extent the risks identified in the assessments of Figure 4.32 and 4.33. This is particularly the case when considering the results for the 'Synergistic' approach to forest management and wood use, since this approach also involves an assumption of enhanced rates of afforestation during the period 2016 to 2030.

Figure 4.34 shows a comparison of estimated potential biomass production from forests in all relevant regions considered in this project, with actual biomass production in 2005 and projected production in 2030 and 2050, for the example of Scenario C1 ('Carry on/imported wood'), and based on the 'Precautionary' approach to forest management and patterns of wood use.

The countries and forest areas in each region in Figure 4.34 have been defined in Table 4.3, Section 4.6.1. The results for the EU27 have already been discussed as part of the previous assessment (see discussion of Figures 4.32 and 4.33). The theoretical long-term maximum potentials for production of biomass (stemwood plus harvest residues) for the CIS region, Canada and the USA are estimated at, respectively, 322, 1 004 and 551 Modt yr^{-1}. Threshold values, based on 70% of these estimates (for rationale see preceding discussion of Figure 4.32) are 226, 703 and 385 Modt yr^{-1}, respectively. For these regions, reported production of industrial roundwood and wood fuel (i.e. forest bioenergy) for the year 2005 is consistently well within the estimated potential production. This is also the case for projected production in 2030. However, in results for the projected production in 2050 for Canada and the USA, there is a significant rise in the level of forest bioenergy production. In the case of the USA, projected total production in 2050 (381 Modt yr^{-1}) approaches the threshold for sustainable-yield wood production. The marked rise in projected production from forests in the USA in 2050, and to a lesser extent in Canada, highlights the points made earlier about the high levels of forest bioenergy supply set to varying degrees in the various 'Carry on' Scenarios, as defined in Task 2. As was the case for the assessment of EU27 forests, these results would also appear to have implications for the setting of target levels of forest bioenergy consumption post 2020, should such targets be set.

It is important to note that the projected increases in forest bioenergy production shown in Figure 4.34 are entirely to meet requirements for supply to the EU region, i.e. there is no allowance for changes in forest bioenergy production to meet increased domestic demand within supplier regions, or from other regions external to the EU. In addition, no explicit allowance has been made in this sustainable-yield assessment for increases in production of industrial roundwood to meet increased demand for material wood products, either domestically or more widely. The projected increases in the supply of industrial roundwood shown in Figure 4.34 for Canada and the USA are specifically related to co-production of material wood products alongside the increased production of forest bioenergy.

As a final point, it should be recalled that the definition of the 'Precautionary' approach to forest management and wood use assumes no forest bioenergy is supplied from the LAM region (i.e. Brazil). A contribution to supply from Brazil to meet a specified target for forest bioenergy consumption in the EU region would involve less domestic production within the EU region and/or less production in other supplier regions such as Canada and the USA.

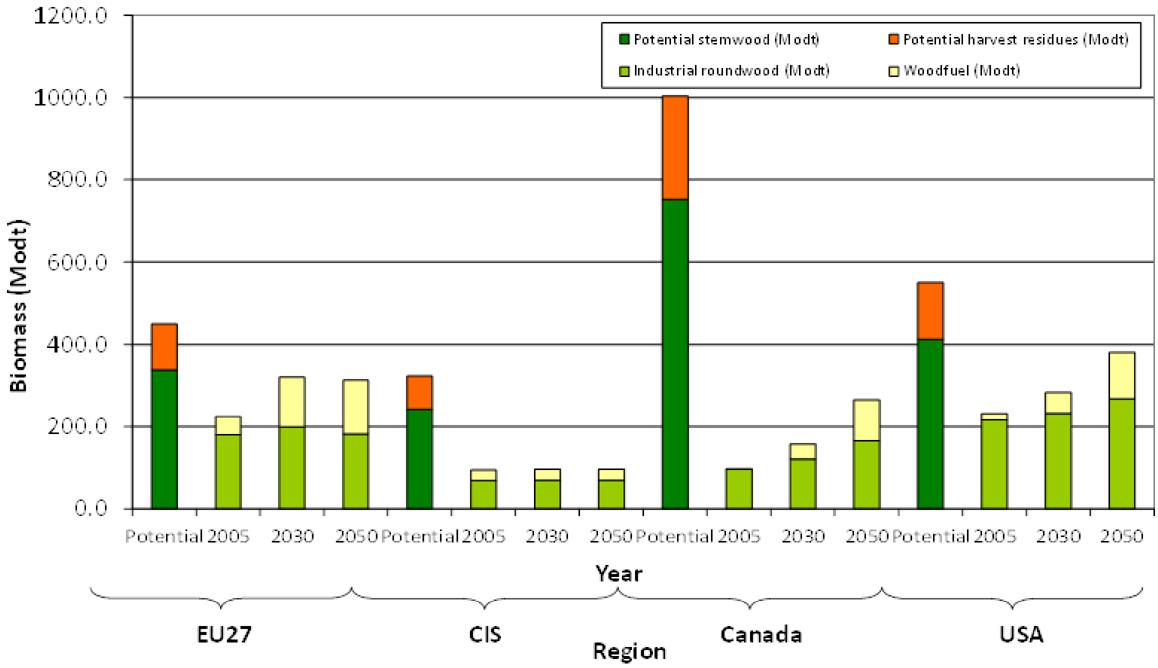

Figure 4.34. Comparison of reported and projected estimates of biomass production from forests with estimates of theoretical maximum potential production, for a range of supplier regions. Results are based on Scenario C1 ('Carry on/imported wood') and the 'Precautionary' approach to forest management and patterns of wood use.

4.10.5. Impacts of bioenergy supply on forest carbon stocks and biogenic carbon emissions

Figures 4.35 and 4.36 show two examples of the projected development of carbon stocks in forests in the EU27 region, as a consequence of changes in forestry practice and patterns of wood use in response to increased requirements for forest bioenergy. For comparison, the figures also show the projected development of forest carbon stocks under the baseline or counterfactual scenario. The example in Figure 4.35 is based on results for Scenario A ('Reference') and the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). Figure 4.36 is also based on Scenario A but involves the 'Synergistic' approach. The simulated result for development of carbon stocks include contributions from:

- Tree biomass
- Litter
- Soil organic matter.
- The results are in units of GtC.

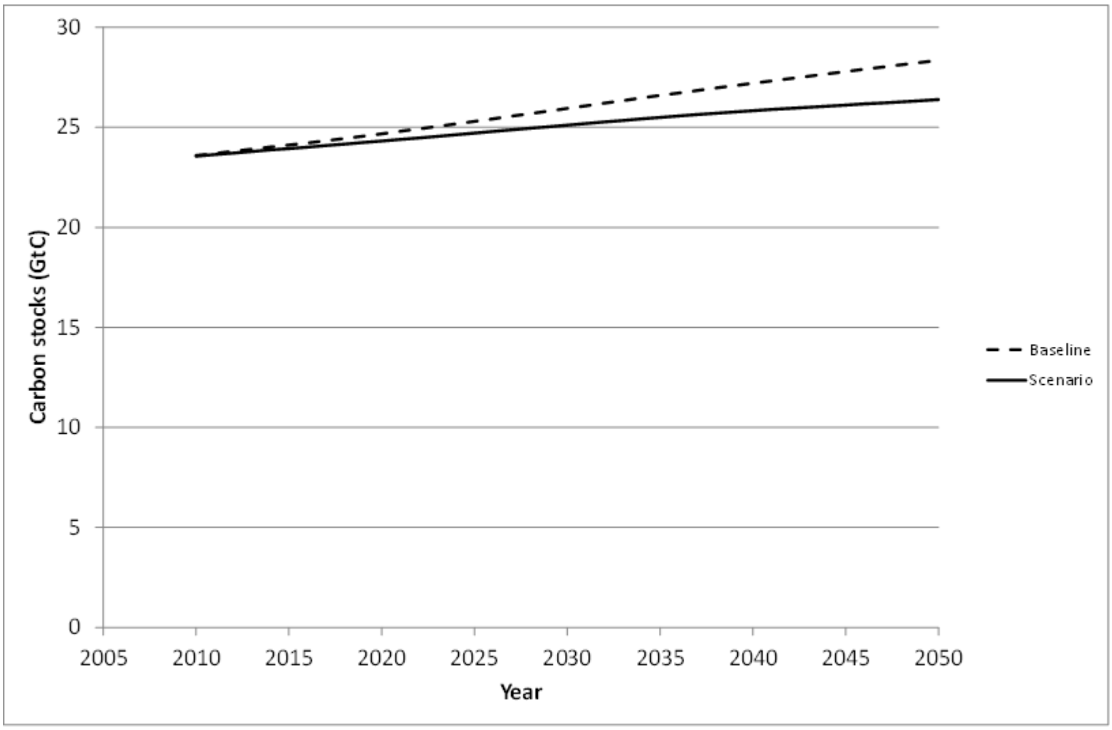

Figure 4.35. Projected development of carbon stocks over time in forests in the EU27 region under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use. A result for the baseline or counterfactual scenario is shown for comparison.

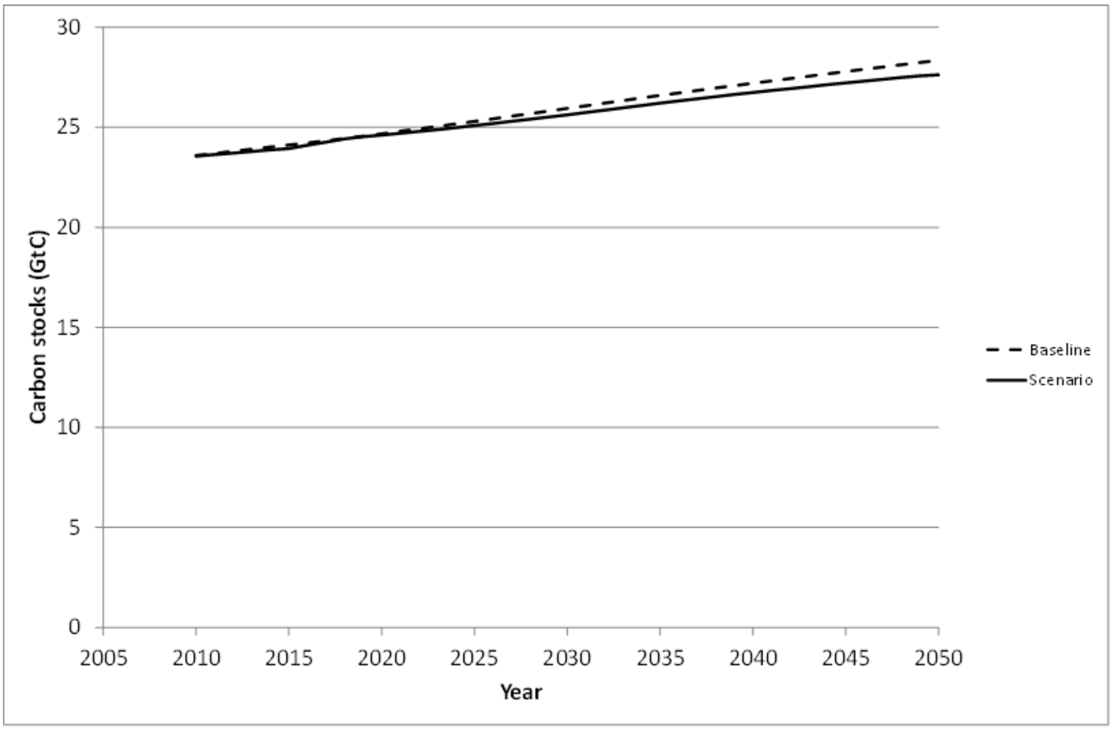

Figure 4.36. Projected development of carbon stocks over time in forests in the EU27 region under Scenario A ('Reference'), subject to the 'Synergistic' approach to forest management and wood use. A result for the baseline or counterfactual scenario is shown for comparison.

The modelling of forest carbon stocks with CARBINE involved providing input data on forest areas, tree species composition, stand ages, growth rates and management practices, as discussed in Sections 4.7 and 4.8. The essential forest inventory data referred to have been summarised in Appendix 9. In Appendix 8, examples are given for how results are produced by CARBINE for a given input dataset, including examples of results for carbon stocks. The modelling of litter and particularly soil carbon stocks required the CARBINE model to be applied quite elaborately, since the dynamics of these carbon pools can involve slow processes and carbon stocks can take many decades to develop. To allow for this, the historical areas of forest in each country were modelled for several centuries prior to the start of the simulation period (effectively the base year of the forest inventory data). The CARBINE model was then applied to simulate the historical development of forest areas and their carbon stocks up to the base year, so as to 'spin up' the results for litter and soil carbon stocks for the start of the simulation period.

In Figure 4.35, carbon stocks in the modelled areas of forest in the EU27 region are estimated to be about 23.5 GtC in the year 2010. Under the baseline or counterfactual scenario, forest carbon stocks are projected to continue to accumulate over the period from 2010 to 2050, reaching a value of about 28.4 GtC in 2050. Under the Reference Scenario A, in which forest bioenergy production is increased in EU27 forests to meet targets for bioenergy consumption set for 2020, forest carbon stocks are still projected to accumulate over the period 2010 to 2050. However, compared with the counterfactual scenario, the accumulation of carbon stocks is reduced, reaching a value of about 26.4 GtC in 2050. A crude estimate of the biogenic carbon emissions associated with forest bioenergy production from EU27 forests under the Reference Scenario A can be inferred from these carbon stock estimates. The difference in carbon stocks for Scenario A and the counterfactual scenario for forest management in 2050 is 28.4 – 26.4 = 2 GtC. This result represents, in very crude terms, the cumulative biogenic carbon emissions associated with bioenergy consumption as represented in Scenario A, over the period 2010 to 2050. Annualising this result over the forty year period, and expressing in units of $MtCO_2$ gives annual emissions due to biogenic carbon between 2010 and 2050 of 183 $MtCO_2$ yr^{-1}. However, as already noted, this estimate is crude. Most importantly, not all of the biomass harvested under Scenario A (or any other scenario) is consumed as bioenergy and therefore combusted, releasing the biogenic carbon within a short interval from the time of harvest. Rather, some of the biomass is converted into material wood products, some of which will have very long service lives, during which the biogenic carbon will be retained out of the atmosphere. As a consequence, it is necessary to allow for the specific timing of emissions due to biogenic carbon in forest bioenergy and associated wood products, and also for any non-CO_2 GHG emissions which may occur when material wood products are disposed of at end of life. These aspects of the LCA calculations were handled in a later stage of the project, as part of the integration of the results from Tasks 2, 3 and 4 into final project results, as described in Section 6.2.

The results in Figure 4.36 may be compared with the results in Figure 4.35. Figure 4.36 is also based on Scenario A but involves the 'Synergistic' approach. As described in Section 4.8.3, the 'Synergistic' approach involves assumptions about positive changes to forest management including:

- Avoiding the introduction of additional harvesting in forest areas with very low growth rates, to protect against slow recovery of carbon stocks after harvesting
- In the EU27 region only, enhanced rates of afforestation post-2015, de-prioritising creation of forest areas with very low growth rates or on organic soils (see Section 4.7.2)
- Where feasible, conservation and enhancement of forest carbon stocks alongside increased harvesting to produce forest bioenergy and materials, through adjustments to existing rotations applied to forest areas managed for production.

These positive forest management interventions have a noticeable effect on the development of forest carbon stocks between 2010 and 2050. Up until about 2030, carbon stocks for Scenario A are almost the same as for the counterfactual scenario for forest management. Between 2030 and 2050, carbons stocks for Scenario A are slightly lower than for the counterfactual scenario, with a carbon stock of 27.6 GtC in 2050. Taking a similar approach to that described for Figure 4.35, biogenic carbon emissions due to Scenario A (for the 'Synergistic' approach) over the period 2010 to 2050 may be very crudely estimated at 73 $MtCO_2$ yr^{-1}. This represents a 60% reduction in biogenic carbon emissions, compared with the 'Precautionary' approach.

Figures 4.37 and 4.38 show two examples of the projected development of carbon stocks in forests in Canada, as a consequence of changes in forestry practice and patterns of wood use in response to increased requirements for forest bioenergy in the EU region. For comparison, the figures also show the projected development of forest carbon stocks under the baseline or counterfactual scenario. The example in Figure 4.37 is based on results for Scenario A ('Reference') and the 'Precautionary' approach to forest management and patterns of wood use (see Section 4.8.3). Figure 4.38 is based on results for Scenario C1 ('Carry on/imported wood') and the 'Precautionary' approach.

The results in Figures 4.37 and 4.38 for Canada show a similar pattern to the results in Figures 4.35 and 4.36 for the EU27 region, but also illustrate the sensitivity of results to levels of projected forest bioenergy supply under different scenarios. For Reference Scenario A, cumulative emissions due to biogenic carbon (as estimated crudely) amount to about 1 GtC. For Scenario C1 ('Carry on/imported wood'), the equivalent result is about 2 GtC, or double the emissions for Scenario A. However, a significant contribution to the biogenic carbon emissions for Scenario C1 is due to the projected pronounced increase in forest bioenergy production between 2030 and 2050. Issues relating to projected levels of forest bioenergy consumption between 2030 and 2050 have been discussed in Section 4.10.4.

As already noted, the estimates of biogenic carbon emissions presented in the preceding discussion are crude. Strictly, it is necessary to allow for the specific timing of emissions due to biogenic carbon in forest bioenergy and associated wood products, and also for any non-CO_2 GHG emissions which may occur when material wood products are disposed of at end of life. These aspects of the LCA calculations were handled in a later stage of the project, as part of the integration of the results from Tasks 2, 3 and 4 into final project results, as described in Section 6.2.

Appendix 11 contains a set of results such as illustrated in Figures 4.35 to 4.38, covering all scenarios, all supplying regions and the 'Precautionary' and 'Synergistic' approaches to forest management and wood use to supply increased quantities of forest bioenergy.

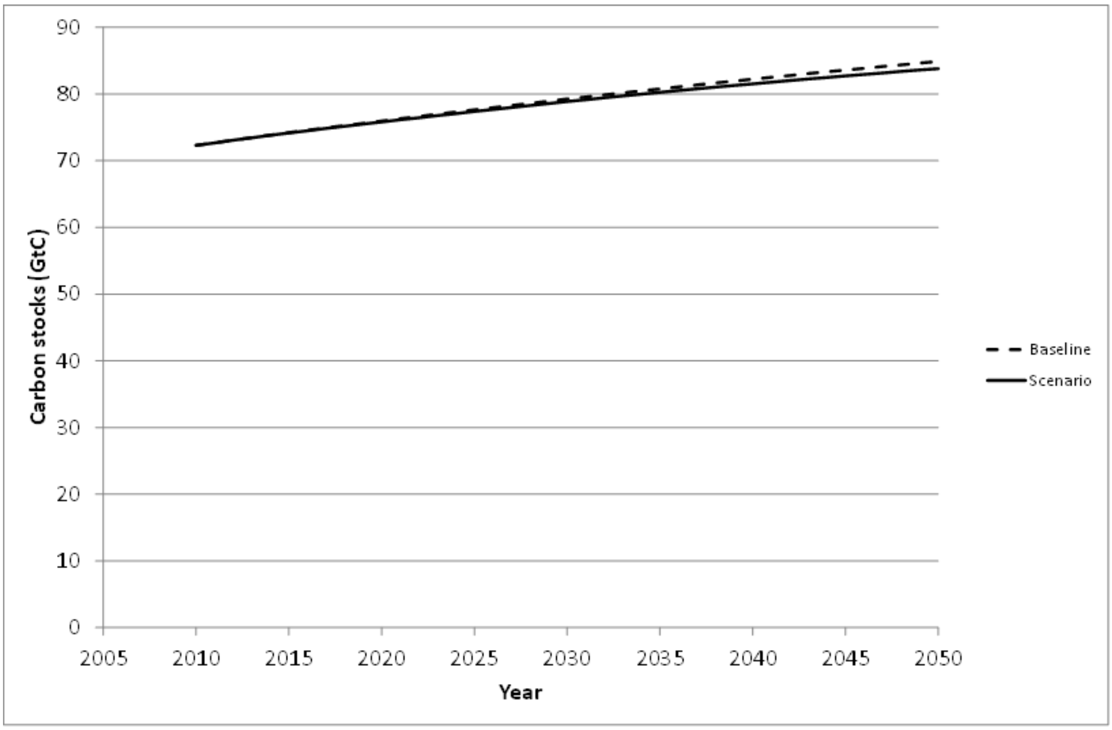

Figure 4.37. Projected development of carbon stocks over time in forests in Canada under Scenario A ('Reference'), subject to the 'Precautionary' approach to forest management and wood use. A result for the baseline or counterfactual scenario is shown for comparison.

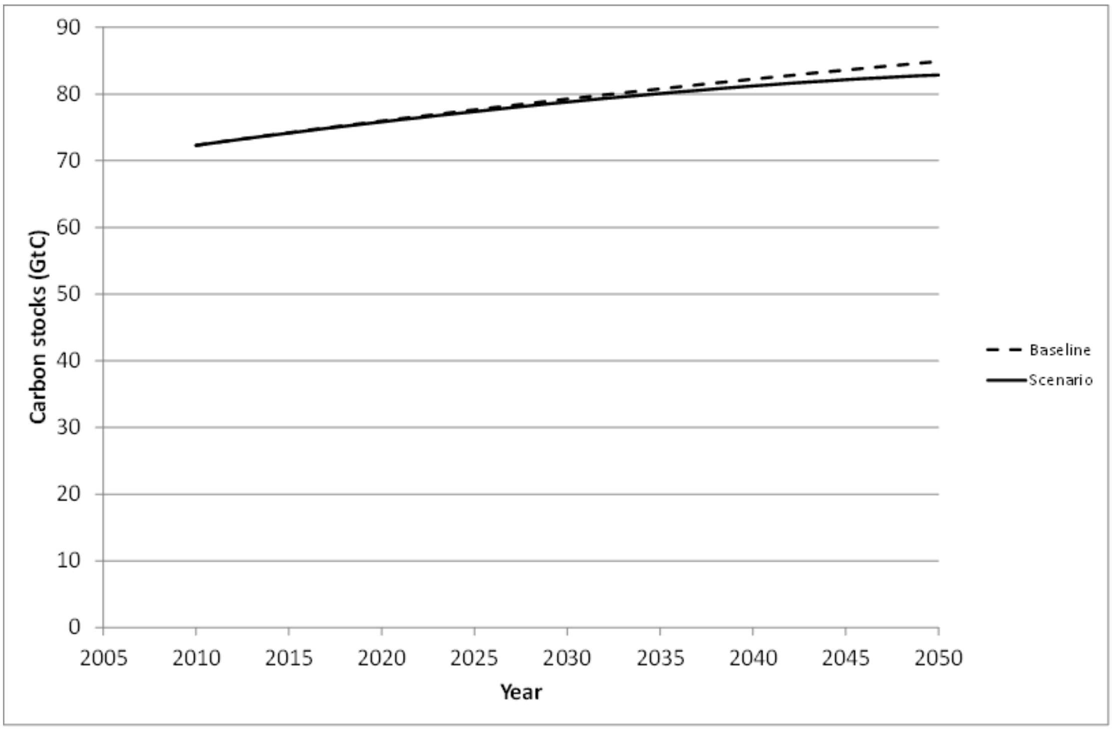

Figure 4.38. Projected development of carbon stocks over time in forests in Canada under Scenario C1 ('Carry on/imported wood'), subject to the 'Precautionary' approach to forest management and wood use. A result for the baseline or counterfactual scenario is shown for comparison.

4.10.6. Approximate biogenic carbon emissions factors

Ideally, an assessment of the carbon impacts of biomass consumption for energy should include the calculation of biogenic carbon emissions factors. Such emissions factors are based on the ratio between the biogenic carbon emissions and the primary energy supplied by a quantity of bioenergy. Indeed, simplistic versions of emissions factors of this type have already been considered in the Introduction section of the Task 1 report for this project (see Table 1.1, Section 1.2 in Matthews *et al*., 2014a). As described in this earlier discussion in the Task 1 report, emissions factors for bioenergy can be compared with equivalent estimates for fossil energy sources. However, strictly, it is not possible to calculate biogenic carbon emissions factors for the forest bioenergy supplied according to the scenarios developed and modelled for the purposes of this project. From a theoretical perspective, the calculation of these types of emissions factors falls outside the scope of the conventions and methods of consequential LCA. From a more practical perspective, the calculation of simple biogenic carbon emissions factors for forest bioenergy sources is problematic for a number of reasons. In particular:

- The emissions factors need to allow not only for the carbon released directly when the wood is combusted for bioenergy, but also for any compensatory sequestration of carbon taking places in relevant forest areas, as well as any additional biogenic carbon emissions taking place in forests, relevant to the production of forest bioenergy, e.g.

due to any consequent changes in carbon stocks that may occur in the remaining trees, litter or soil. These various contributions towards overall biogenic carbon emissions have been modelled comprehensively in this study. However, the existence of several potential contributions to biogenic carbon emissions, in addition to those released directly when wood is burnt, can cause problems for calculating simple emissions factors (e.g. see next point).

- In many situations (see Sections 2.5 to 2.7 of the Task 1 report for this project), the production and supply of forests bioenergy involves a complex web of wood production and processing flows, including co-production of material wood products, or possibly diversion of the supply of wood away from use for material wood products, to use as forest bioenergy instead. In such situations, the calculation of biogenic carbon emissions factors becomes complicated, because it is necessary to allocate the emissions amongst a number of energy and material co-products, and also to allow for any diversion of wood away from use for materials. The methodology for carrying out such an allocation of biogenic carbon emissions as part of consequential LCA is not straightforward and requires knowledge of GHG emissions associated with all co-products and counterfactuals.
- Emissions factors specifically for forest bioenergy sources (as calculated approximately to produce the results presented in this section) may misrepresent the overall impacts of GHG emissions associated with the production of forest bioenergy sources alongside material wood co-products (which may displace emissions-intensive non-wood materials, or materials with lower emissions intensities). Conversely, the emissions factors for bioenergy may not reflect deleterious or beneficial impacts on GHG emissions due to increased use of material non-wood materials, in situations where the supply of wood is diverted from use for material products to use as a source of energy. Similarly, the impacts on GHG emissions due to changes in patterns related to the disposal of material wood co-products, or non-wood counterfactuals, may be poorly represented.
- Biogenic carbon emissions factors for forest bioenergy are not a constant parameter, but are variable over time, in response to the specific details of the timing of harvesting/extraction events and any responses in the (highly non-linear) carbon dynamics of relevant forest areas (this has been discussed at length in the Task 1 report for this project). Hence, it is necessary to consider the development of biogenic emissions factors for forest bioenergy over time, and/or to consider average emissions factors over a specified time period or time horizon.

It follows that simple biogenic carbon emissions factors for forest bioenergy sources are typically very difficult (or strictly impossible) to calculate, and the derivation of estimates for biogenic carbon emissions factors should not really be attempted, or should only be undertaken with extreme caution and with strong caveats attached to any results.

Despite the preceding strong cautionary remarks, to assist with understanding the assessment of biogenic carbon emissions for forest bioenergy sources undertaken in this project, it was decided to attempt to calculate what may be very approximate biogenic carbon emissions factors for the supply of forest bioenergy sources, as modelled in Task 3 of this project, for the six scenarios developed in Task 2. It is important to understand that the calculation of these emissions factors involved certain assumptions, which may represent significant over-simplifications in many situations, notably:

- Biogenic carbon sequestration and emissions occurring in forest areas in response to harvesting and production were allocated between forest bioenergy sources and any directly associated (additional) material wood co-products on a simple oven-dry (wood) mass basis.
- To allow for time lags that can occur in forest dynamics (for both emissions and sequestration), the mass-based allocation coefficients were calculated on a cumulative basis. For example, for calculating emissions factors for the year 2012, the allocation coefficient was calculated by referring to the sum of masses of forest bioenergy produced in 2010, 2011 and 2012, and the sum of the masses of wood used for any associated (additional) material wood products in 2010, 2011 and 2012.
- In situations where wood supply was diverted from use for material wood products to use for energy, 100% of the biogenic carbon emissions were allocated to the forest bioenergy (this may under-estimate or possibly over-estimate the actual total GHG emissions associated with the forest bioenergy, see earlier in this discussion).
- In situations where additional material wood products were co-produced in association with forest bioenergy, the displacement of GHG emissions due to the use of material wood products in place of counterfactuals was not allowed for (this may over-estimate or possibly under-estimate the actual total GHG emissions associated with the forest bioenergy, see earlier in this discussion).

It must be stressed that the biogenic carbon emissions factors for forest bioenergy calculated in this way must be regarded as very approximate and interpreted with considerable caution.

Two types of biogenic carbon emissions factors were estimated, for a sequence of years from 2010 to 2050:

1. Annual emissions factors, based on annual results for (allocated) biogenic carbon emissions and annual quantities of primary energy supplied as forest bioenergy
2. Cumulative emissions factors, based on cumulative (allocated) biogenic carbon emissions and cumulative quantities of primary energy supplied as forest bioenergy, calculated over a period from 2010 up to and including the year for which the emissions factor applies. For example, when calculating a cumulative emissions factor for the year 2020, this involved referring to cumulative results for biogenic carbon emissions and primary energy supply over the period 2010 to 2020. Whilst noting the strong caveats stated earlier in this discussion, the biogenic carbon emissions factors calculated in this way for the year 2050 may be of particular interest (see Section 5 of the Task 1 report for this project, in particular Section 5.2.1).

Figures 4.39 to 4.46 show some examples of estimated trajectories for biogenic carbon emissions factors for forest bioenergy, as supplied from different sources under the scenarios developed in this project. Figures 4.39 to 4.42 show four examples of results for annual biogenic carbon emissions factors for the cases:

- Figure 4.39 – forest bioenergy produced in the EU27 under Scenario C3 ('Carry on/domestic wood') and for the 'Precautionary' approach to forest management and wood use
- Figure 4.40 – forest bioenergy produced in the EU27 under Scenario C3 ('Carry on/domestic wood') and for the 'Synergistic' approach to forest management and wood use
- Figure 4.41 – forest bioenergy produced in Canada and supplied to the EU under Scenario C1 ('Carry on/imported wood'), and for the 'Precautionary' approach to forest management and wood use
- Figure 4.42 – forest bioenergy produced from forest plantations in the LAM region (i.e. Brazil) and supplied to the EU under Scenario C1 ('Carry on/imported wood') and for the 'Synergistic' approach to forest management and wood use

Figures 4.43 to 4.46 show, respectively, results equivalent to those in Figures 4.39 to 4.42 but for cumulative biogenic carbon emissions factors.

All of these figures also display basic (fossil carbon) emissions factors for coal, oil and natural gas, to permit comparison with the results for the biogenic carbon emissions of forest bioenergy. (These values for fossil energy sources have been presented and discussed previously in Table 1.1, Section 1.2 of the Task 1 report for this project.) The examples in these figures have been selected to illustrate results associated with high forest bioenergy consumption based on contrasting sources or forest management approaches.

Appendix 11 contains a set of results such as illustrated in Figures 4.39 to 4.46, covering all scenarios, all supplying regions, and the 'Precautionary' and 'Synergistic' approaches to wood use.

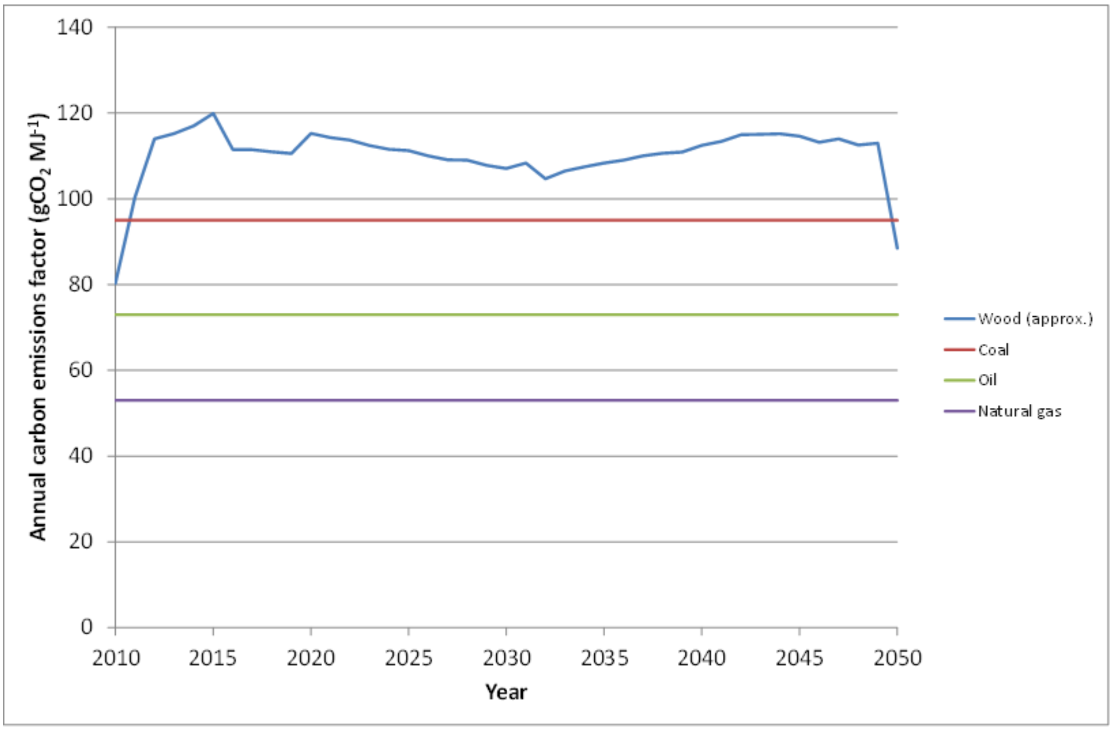

Figure 4.39. Projected development of approximate annual biogenic carbon emissions factor for forest bioenergy sources supplied by forests in the EU27 region under Scenario C3 (Carry on/domestic wood'), subject to the 'Precautionary' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

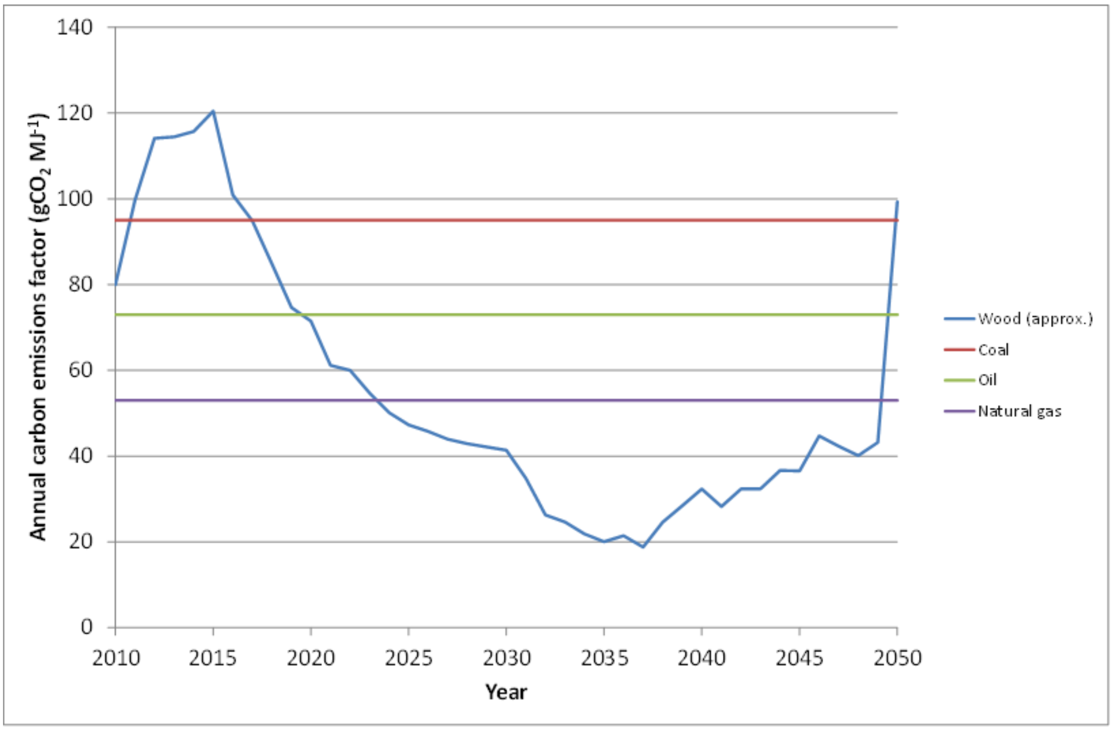

Figure 4.40. Projected development of approximate annual biogenic carbon emissions factor for forest bioenergy sources supplied by forests in the EU27 region under Scenario C3 (Carry on/domestic wood'), subject to the 'Synergistic' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

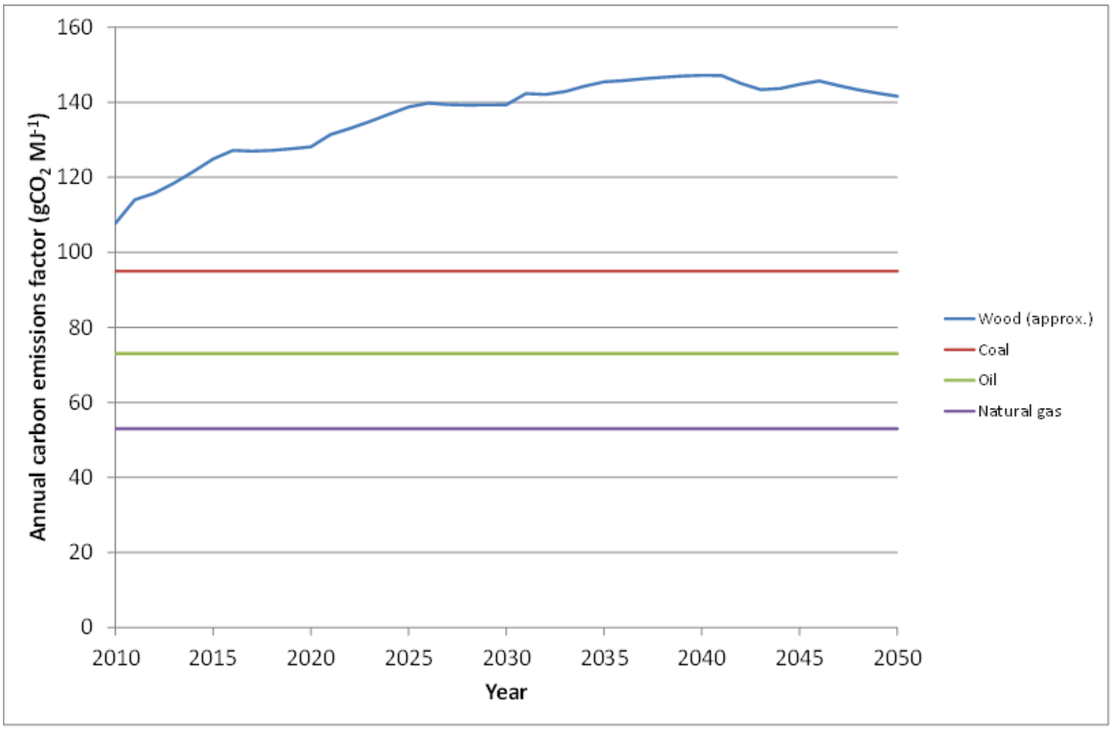

Figure 4.41. Projected development of approximate annual biogenic carbon emissions factor for forest bioenergy sources supplied by forests in Canada to the EU region under Scenario C1 (Carry on/imported wood'), subject to the 'Precautionary' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

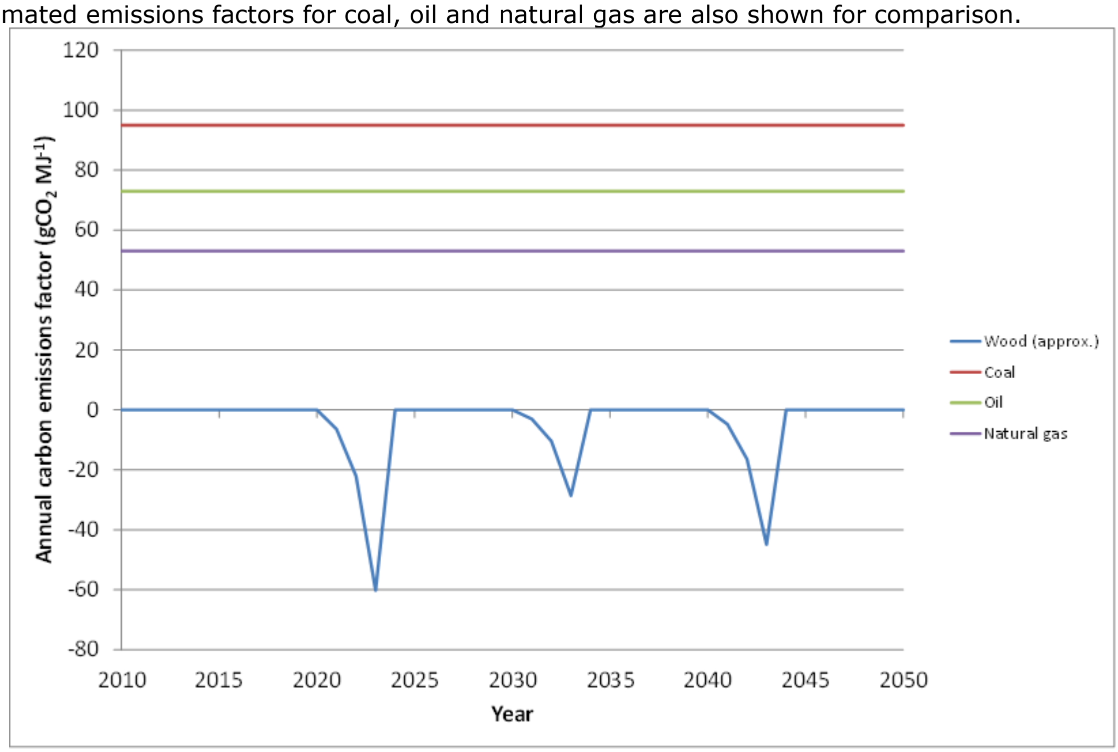

Figure 4.42. Projected development of approximate annual biogenic carbon emissions factor for forest bioenergy sources supplied by plantation forests in Brazil to the EU region under Scenario C1 (Carry on/imported wood'), subject to the 'Synergistic' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

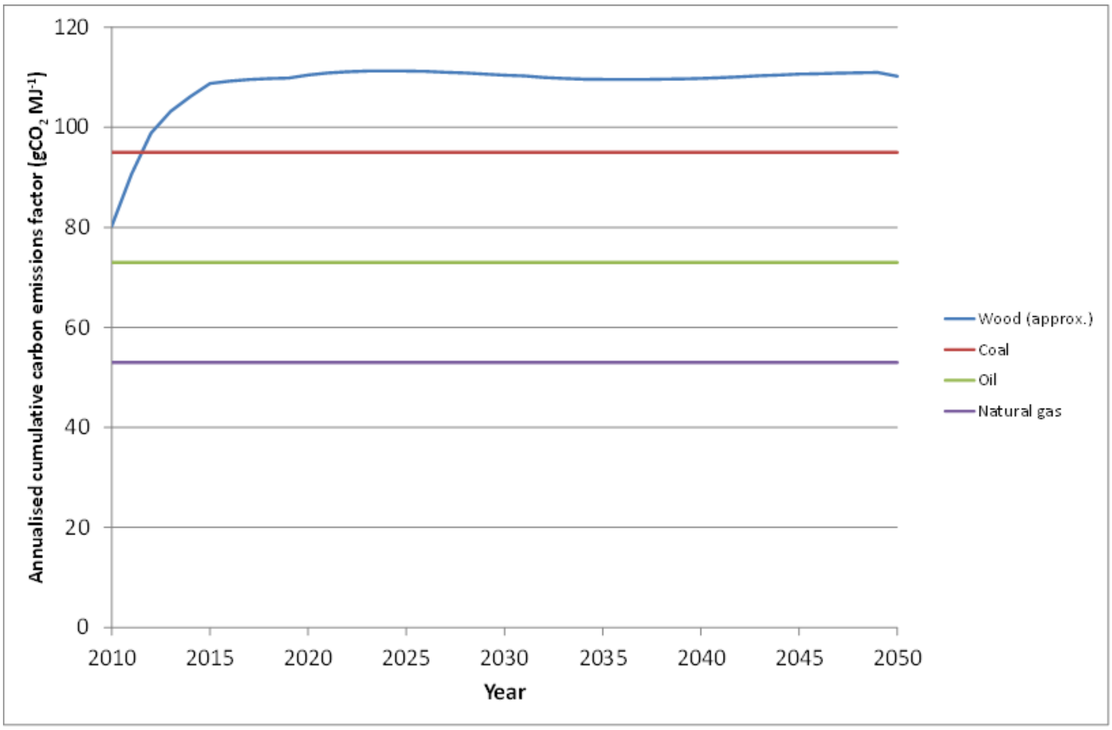

Figure 4.43. Projected development of approximate cumulative biogenic carbon emissions factor for forest bioenergy sources supplied by forests in the EU27 region under Scenario C3 (Carry on/domestic wood'), subject to the 'Precautionary' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

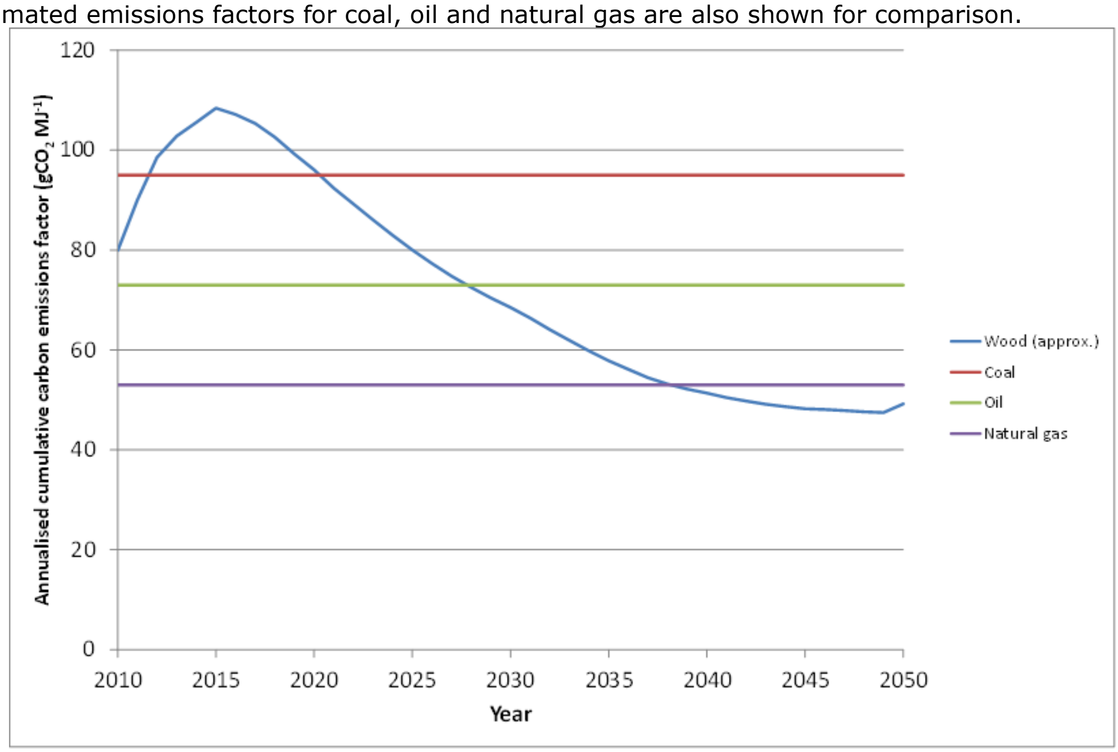

Figure 4.44. Projected development of approximate cumulative biogenic carbon emissions factor for forest bioenergy sources supplied by forests in the EU27 region under Scenario C3 (Carry on/domestic wood'), subject to the 'Synergistic' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

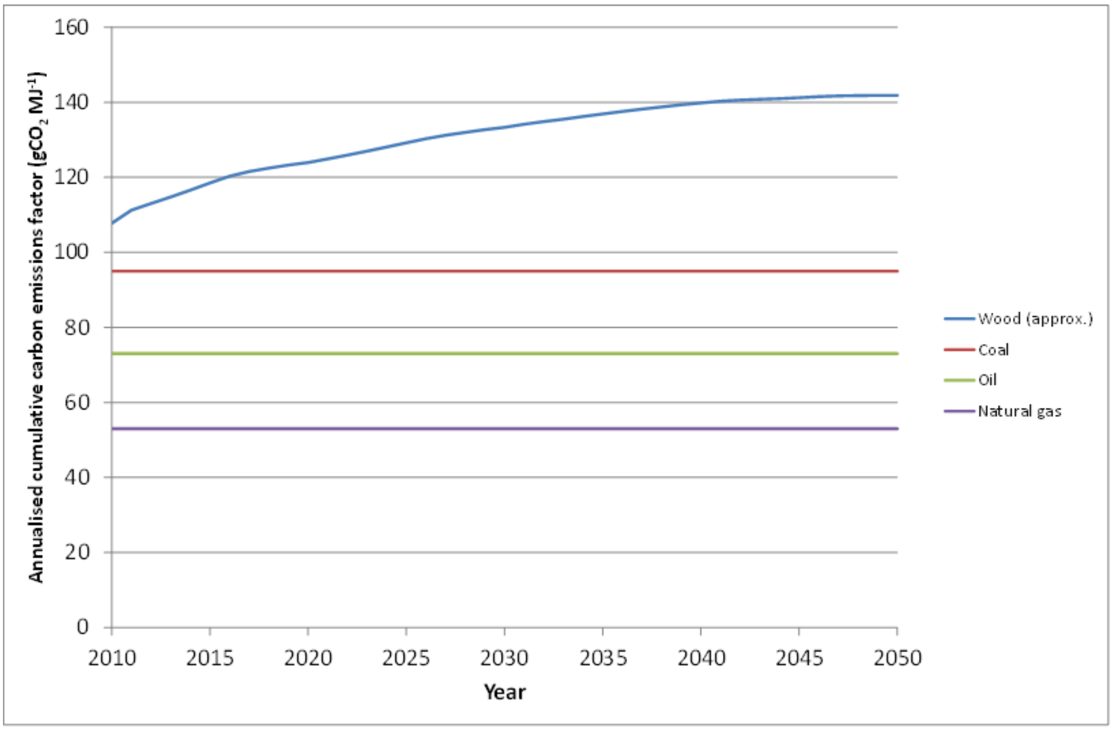

Figure 4.45. Projected development of approximate cumulative biogenic carbon emissions factor for forest bioenergy sources supplied by forests in Canada to the EU region under Scenario C1 (Carry on/imported wood'), subject to the 'Precautionary' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

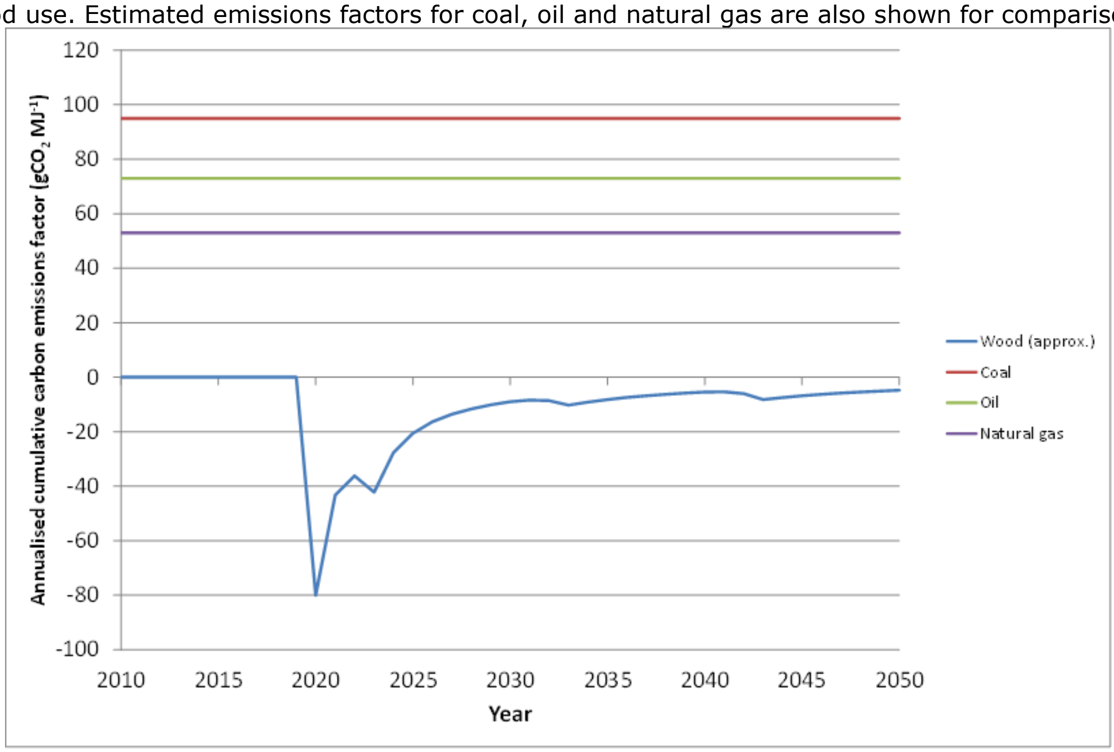

Figure 4.46. Projected development of approximate cumulative biogenic carbon emissions factor for forest bioenergy sources supplied by plantation forests in Brazil to the EU region under Scenario C1 (Carry on/imported wood'), subject to the 'Synergistic' approach to forest management and wood use. Estimated emissions factors for coal, oil and natural gas are also shown for comparison.

A number of points can be drawn from consideration of the results in Figures 4.39 to 4.46:

- The magnitudes (and even the sign) of biogenic carbon emissions factors vary considerably over time. This is most evident in the results in Figures 4.40 and 4.44, which exhibit the characteristic pattern for increased production of forest bioenergy, i.e. initially high biogenic carbon emissions, followed by a progressive reduction in magnitude (see for example Sections 3.6, 3.9, 4.9 and 5 of the Task 1 report for this project). The high emissions factors observed in the results for the EU27 ('Precautionary' approach, Figures 4.39 and 4.43) and for Canada (Figures 4.41 and 4.45) should also eventually decline to a much smaller magnitude than shown in the figures. However, this has not occurred over the time horizon to 2050. The moderate negative emissions factors associated with forest bioenergy supplied from Brazilian plantations also decline in magnitude over time. (Essentially, this is because the same processes determining the forest carbon dynamics are involved in all cases.)
- There can be short-term fluctuations in results for annual emissions factors. This is particularly apparent in the results for the EU27 (Figures 4.39 and 4.40). However, these fluctuations are of less significance than the average magnitude (and sign) of biogenic carbon emissions over longer time periods.
- Emissions factors for the different sources modelled in this project are very variable, ranging from approximately 1.5 times that of coal (Figure 4.41 and 4.45) to moderately negative (Figures 4.42 and 4.46).
- The example results for the EU27 (Figures 4.39 and 4.40, and Figures 4.43 and 4.44) strongly suggest that emissions factors can be highly sensitive to the approaches taken to forest management and wood use.

The results for biogenic carbon emissions factors in Figures 4.39 to 4.46, and in Appendix 11, also raise certain key questions, specifically:

- Given the considerable variability in outcomes for carbon impacts of forest bioenergy, when expressed as approximate biogenic carbon emissions factors, how might the production of forest bioenergy be managed, to avoid or minimise high biogenic carbon emissions, and/or to increase the likelihood of lower or negative biogenic carbon emissions?
- Given the assumptions underlying the definition of the 'Precautionary' approach to forest management and wood use, why are the biogenic carbon emissions factors high in many cases (see Appendix 11)? Furthermore, why are biogenic carbon emissions factors also sometimes high in results for the 'Synergistic' approach to forest management and wood use, notably for forest bioenergy imported from North American sources, given the way the 'Synergistic' approach was defined (see Section 4.8.3)?

The question of whether it is possible to identify and favour low-risk bioenergy sources, and similarly identify and disfavour high-risk bioenergy sources, has been a central subject of this project, and has received considerable attention in Task 1 and the associated report (Matthews *et al.*, 2014a). Absolute certainty in any answer to the question is likely to be elusive, but the attempt in this project to clarify and distinguish low-risk and high-risk bioenergy sources, has led to the development of the provisional forest bioenergy decision tree, introduced in Figures 2.1a-d, in Section 2.4 of this final project report. Further work may be needed on this decision tree, in particular, some further clarifications, amendments or elaborations may be needed in order for it to attract wide acceptance amongst stakeholders. It must also be acknowledged that the decision tree is quite large and has many possible options and branches. Nevertheless, the approach is systematic and the choices amongst forest bioenergy sources should be reasonably clear. At least in principle, an approach to screening sources of forest bioenergy for high or low risk with regard to GHG emissions could represent one possible way of addressing the first of the questions posed above.

With regard to the second question, it is important to understand the purpose in this project behind referring to the ‘Precautionary’ approach and ‘Synergistic’ approach to forest management and wood use, and their definition. The definitions for these approaches are given in Section 4.8.3 of this report. As explained in that discussion, the essential purpose of the ‘Precautionary’ approach has been to represent a “plausible set of changes” in forest management and wood use to supply quantities of forest bioenergy in the EU. As such, some, but not all, high-risk options for forest bioenergy supply are excluded. In particular, the inclusion of the option of introducing management for production in forest areas where this was not previously practiced has a big influence on biogenic carbon emissions. In the modelling of changes in forest management in Canada, the area of such forest contributing to increased forest bioenergy production is relatively large (see Section 4.8.4), and this represents a major reason for the high biogenic carbon emissions factors estimated for Canada (see an illustration of this point in Section 3.6.3 of the Task 1 report for this project). This also applies in the modelling of changes in forest management in the USA, but to a lesser extent.

If production of forest bioenergy were to be increased in these regions in different ways to those assumed in the modelling for this project then, potentially, rather different results might be obtained. This might be the case, for example, if forest bioenergy production were to be based principally on the utilisation of early thinnings from areas of forest already under management for production, alongside the extraction of harvest residues (within constraints to avoid depletion of the nutrient status of forest stands, and other negative impacts, see Figure 2.1c, Section 2.4). The modelling of such a scenario, along with other possible options as part of a wider sensitivity analysis, could be the subject of further research. However, in the absence of specific controls or criteria for the production and supply of forest bioenergy, there was no basis for assuming a stronger prioritisation of production of forest bioenergy from low-risk and moderate-risk sources over certain high-risk sources, as part of the specification of the 'Precautionary' or 'Synergistic' approach. Furthermore, the introduction of management for production in forest areas where this was not previously practiced can involve net reductions in GHG emissions, if this involves co-production of bioenergy in conjunction with material wood products. However, this is not guaranteed unless the material wood products displace counterfactual products that are GHG-intensive, and are disposed of at end of life with low associated GHG emissions (Matthews *et al.*, 2014b). The results in Figures 4.39 to 4.46 and the associated discussion strongly imply a requirement for tighter criteria on types of forest management and wood sources involved in the supply of forest bioenergy.

The changes in forest management assumed to be involved in forest bioenergy supply under the 'Synergistic' approach also include the introduction of management for production in forest areas where this was not previously practiced, but with a greater emphasis on co-production of material wood products alongside forest bioenergy. However, as highlighted earlier in this discussion, the approximate biogenic carbon emissions factors for forest bioenergy, as calculated and presented here, do not properly allow for the GHG impacts of co-products (either positive or negative), including due to their utilisation in place of counterfactuals and their disposal at end of life. (This is also true for the results based on the 'Precautionary' approach.) If material wood co-products can be effectively utilised to displace GHG-intensive counterfactual materials, and if they can be recycled or disposed of effectively at end of life, in terms of GHG emissions, then, overall, the co-production of forest bioenergy alongside material wood products can result in significant net reductions in GHG emissions (Matthews *et al.*, 2014b). However, the development of policies and measures to ensure the effective utilisation and recycling/disposal of material wood products represents a challenge in itself, and further consideration of this issue is outside the scope of this project. In the absence of such policies or measures, the analysis of sensitivities in the final project results in Sections 6.7 to 6.9.4 of this final project report suggests that outcomes in terms of overall GHG emissions may be very variable.

Certain detailed assumptions underlying the 'Synergistic' approach also influence the results for biogenic carbon emissions factors estimated for different regions. This is notably the case for any assumptions about the potential for enhanced rates of afforestation and for the enrichment of carbon stocks in forest stands.

Assumptions concerning afforestation varied considerably with region. For the EU27 region, it was possible to estimate areas of land available for afforestation by individual Member states, constrained to avoid risks of iLUC (see Sections 4.7.1 and 4.7.2, in particular Table 4.4). Consequently, the potential for afforestation activities, as an explicit complement to increased forest bioenergy production, could be represented in the assumptions made for the EU27. For certain other regions (CIS, Canada, USA), estimates could not be derived for land areas potentially available for afforestation, particularly when allowing for the avoidance of risks of iLUC. Hence, it was necessary to take a very conservative approach towards assumptions about the potential for enhanced afforestation activities in these regions, i.e. there was no enhancement over the business-as-usual projection of afforestation rates, as assumed in the modelling of both the baseline for forest management and in the 'Precautionary' approach (see Table 4.9, Section 4.8.3). An exception was the LAM region, specifically the country of Brazil, for which there was information on land areas available for afforestation, and also on existing precedents for a market response to increased demand for forest biomass (see Section 4.8.3 and Box 4.1). However, some uncertainty should be noted in the modelling of forests and bioenergy production in Brazil, specifically with regard to counterfactual land use (see Section 4.8.3 and in particular Note 1 to Table 4.9).

The representation of potential for activities to enrich carbon stocks (and productive potential) in forest stands, as a complement to forest bioenergy production, was effectively restricted to the EU27 region. Some data were available for EU Member States on areas of forests managed on relatively short rotations, or as coppice. In some cases, this current management represents a response to historical degradation or over-exploitation of what were previously high forest stands. In some cases, these forest areas were represented explicitly in forest inventory information (e.g. such as in the EFISCEN database, see Table 4.2, Section 4.5.2). In these cases, it was possible to model the potential impacts on carbon stocks that would occur if these areas were to be progressively restored to high forest. With relatively minor exceptions, such an approach was not possible in other geographical regions (specifically the CIS, Canada and the USA), because it was not possible to identify forest areas where such measures might be taken.

Before concluding this discussion of approximate biogenic carbon emissions factors for forest bioenergy, it is important to highlight a key feature in the results produced by this project. Several of the scenarios developed in Task 2 of this project are intended to represent possibilities for increasing the consumption of forest bioenergy in the EU post 2020 (i.e. Scenarios B, C1, C2 and C3). As illustrated in Figure 4.13 in Section 4.8.2, a critical common feature of these scenarios is that the projected level of forest bioenergy supplied to the EU over the period 2020 to 2050 increases to a significant degree over the period, and the increase is greatest for the period 2040 to 2050. It should be noted that this common pattern in the results is related to assumptions made in the modelling of scenarios using the VTT-TIAM model, notably about cost-supply curves, the development of the carbon price over time, and constraints (or the lack of them) on potential for biomass supply from forests (see discussion of Task 2 in Section 3). The generally progressive increase in the level of forest bioenergy supply from 2020 to 2050, as projected under these scenarios, particularly towards the end of this period, has the effect of driving a concomitant progressive increase in wood harvesting from forest areas, requiring related changes in forest management and wood use, with consequent incremental impacts on the development of forest carbon stocks, hence on biogenic carbon emissions. Essentially, the continual increase in the level of forest bioenergy production means that forest carbon balances do not have time to recover over the period 2020 to 2050. This suggests the question, what if the supply of forest bioenergy were to be allowed to increase, but only up to 2030, or possibly 2040, but then constrained not to increase further from that point? An even more refined approach might be possible, for example allowing the supply of some forest bioenergy sources to increase only up to 2020, some to increase to 2030 and others up to 2050. The modelling of such refined scenarios could be a subject for further research.

Finally, the very approximate nature of the biogenic carbon emissions factors discussed in this section must be stressed again. Strictly, to properly assess the carbon impacts of forest bioenergy use, it is necessary to allow for:

- Indirect emissions associated with forest bioenergy production, supply and conversion
- Biogenic carbon and GHG emissions which occur when material wood co-products are produced, utilised and disposed of at end of life, along with GHG emissions associated with counterfactuals displaced by wood products.

These aspects of the LCA calculations were handled in a later stage of the project, as part of Task 4 (see Section 5) and in the integration of the results from Tasks 2, 3 and 4 into final project results, as described in Section 6.2. Refined assessments of GHG emissions impacts for forest bioenergy sources are considered in Section 6.6, 6.7 and 6.9.4.

5. Assessment of non-biogenic GHG emissions

5.1. Purpose

The purpose of this section is to describe the approaches taken in Task 4 of this project, to determine GHG emissions that have not been addressed elsewhere in this assessment of the carbon impacts of the different scenarios developed in Task 2. In particular, this concerns indirect GHG emissions associated with the cultivation of energy crops, with forest operations, with the production and use of all other sources of biomass, and with all relevant counterfactuals. In this context, counterfactuals are products, the production or displacement of which, have been affected by biomass generated in each scenario. Additionally, for completeness, indirect emissions associated with the import of non-biomass energy into EU27, consisting of fossil and nuclear fuels, and electricity, had to be taken into account. The reason for this is that, for consistency with national GHG inventory reporting requirements, the VTT-TIAM model represents for GHG emissions within the borders of the EU27. However, since this project involves application of consequential LCA on a global scale (see Section 1.2.2), it is necessary to account for GHG emissions which occur outside the EU27 borders but were generated due to the demand for energy within these borders.

5.2. Approach

The starting point for work on Task 4 involved North Energy Associates assembling a database of GHG emissions factors for products and services. Such emissions factors were needed for the evaluation of indirect GHG emissions of relevant pathways associated with the provision of fossil and nuclear fuel imports to the EU27, and the production and use of bioenergy provided by imports and supplied from sources within the EU27. Subsequent evaluation was undertaken and recorded in MS Excel workbooks to provide necessary functionality and transparency. Ideally, emissions factors needed represent the provision of specified products and services in relevant countries for the time period under consideration. However, this posed a number of challenges which had to be addressed by practical solutions.

The first challenge was the very large number of products and services for which emissions factors were required. This is due to the considerable diversity of the pathways that had to be taken into account. The second challenge was that the VTT-TIAM model specifies global regions, some of which consist of groups of individual countries. With respect to bioenergy supply and trade in particular, these regions consist of the EU27 region; LAM or Latin America (countries of Central and South America); ODA or Other Developing Asia (including Indonesia and Malaysia); CIS or Commonwealth of Independent States (mainly former-Soviet Union); USA or the United States of America; and CAN or Canada. Apart from the EU27, the USA and Canada, emissions factors are not generally available for these regions. Hence, it was necessary to designate potentially-representative countries such as Argentina or Brazil, depending on circumstances, for the LAM region, and Russia for the CIS region. The third major challenge was that emissions factors were needed for the time period between 2010 and 2050. In some but not all instances, suitable emissions factors were available for 2010, 2020 and 2030. However, it must be appreciated that emissions factors for future years are necessarily speculative and based on specific forecasts or assumptions.

Within the context of these considerations and constraints, a suitable emissions factor database (EFD.xlsx) was assembled. This database consists of emissions factors for 248 relevant products and services derived from a number of different sources, of which the Global Emissions Model for Integrated Systems (GEMIS Version 4.9) database was the most prominent source (IISA, 2014). The main reason for this was that the GEMIS database contains many emissions factors for relevant products and services, especially for the EU27 and, in some major instances, for 2010, 2020 and 2030. Another attractive feature of the GEMIS database is that it provides emissions factors that are disaggregated into carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions. This allowed emissions factors to be applied with specified values of Global Warming Potentials (GWPs) to ensure consistency in the preparation of MS Excel workbooks for all the pathways addressed in this project.

In some circumstances, the GEMIS database did not provide emissions factors for certain products and services in the EU27 or for 2010, 2020 and 2030. However, emissions factors were often available for Germany and, hence, on occasion, these were adopted as surrogate values for the EU27 region. A number of other sources were used for emissions factors to ensure that all relevant products and services were covered adequately. These sources included Inter-governmental Panel on Climate Change (IPCC) guidelines for national GHG emissions inventories (IPCC, 2006; IPCC, 2007; IPCC, 2008) for combustion emissions factors, the European Reference Life Cycle Database (ELCD) Version 3.0 for a range of specific products and services (ELCD, 2014), and European Fertilizer Manufacturers’ Association (EFMA) for emissions factors of artificial fertilisers (Brentrup and Palliére, 2008). In some cases, emissions factors were only available for 2010 or earlier years. In the absence of any other data, these were adopted for 2020 and 2030 without any adjustment although it was appreciated that this may over-estimate emissions for these future years as reductions might be expected in GHG emissions.

The EFD contains significant transparency, particular regarding reference to the sources of the emissions factors it contains. Additionally, it has essential functionality since basic data are converted by selected GWPs into total GHG emissions factors, presented in units of equivalent (eq.) CO_2, for a selected year of 2010, 2020 and 2030. These GHG emissions factors each have unique cell names to assist their use in subsequent workbooks for the evaluation of indirect GHG emissions associated with relevant pathways. In particular, this enables results to be generated automatically for any year (2010, 2020 or 2030) specified in these workbooks. Additionally, this helps with the updating of emissions factors in the EFD. As well as emissions factors, the EFD contains standard factors and conversion factors. The standard factors include values for GWPs, and the density and net calorific values of necessary fuels. Conversion factors are provided for commonly-quoted units of length, volume, mass and energy. The given values of standard and conversion factors have filenames which enables them to be applied accordingly in subsequent pathway workbooks.

The VTT-TIAM model dictated the pathways that needed to be represented for the complete evaluation of indirect GHG emissions. Total GHG emissions, disaggregated into CO_2, CH_4 and N_2O emissions, were provided by the VTT-TIAM model for the EU27 region, for each of the scenarios considered here. Fossil fuel combustion forms the main source of these GHG emissions. However, it is also known that other sources of emissions, such as CH_4 emissions from coal mining and natural gas transportation, and N_2O emissions from usual agricultural activities, are included in the estimates generated by the VTT-TIAM model for the EU27 region. In general, the VTT-TIAM model represents direct GHG emissions associated with activities within the borders of the EU27 region. In relation to this project, this means that a number of potentially-important sources of GHG emissions are missing from the GHG emissions estimates of the VTT-TIAM model. In particular, relevant GHG emissions which occur outside the EU27 region due to the import of any type of energy are excluded from the VTT-TIAM model estimates. Additionally, all GHG emissions, either within or outside the EU27 region, associated with the supply of bioenergy to the EU27 region are not represented in the VTT-TIAM model. This exclusion also applied to any counterfactuals related to bioenergy supplies. Consequently, it was necessary to address all these pathways in evaluating indirect GHG emissions.

A summary of the pathways that had to be considered in evaluating indirect GHG emissions is given in Table 5.1. Non-biomass energy imports into the EU27 region consist of fossil and nuclear fuels as well as electricity. The fossil fuels comprise both basic and finished fuels whereas nuclear fuels were assumed to be processed uranium. Emissions factors for these imports, which include production outside the EU27 region and transportation to the EU27 region, were obtained by North Energy Associates from the GEMIS database (for details, see Section 5.5).

Wood fuel imports to the EU27 region were assumed to be wood pellets derived from forests. The CARBINE model was used by Forest Research to determine changes in carbon stocks and sequestration, and biogenic carbon (see Section 4), and also GHG emissions associated with the forest operations that provide wood at the roadside in the forest (see Section 5.4). North Energy Associates undertook development of the workbook representing GHG emissions associated with transportation of wood from the roadside in the forest, conversion to wood pellets and transportation to the borders of the EU27 region. A similar approach was adopted for the evaluation of wood fuel production within the EU27 region but with coverage of wood chips as well as wood pellets. The supply of wood fuel from both within and outside the EU27 region is represented in one workbook (see Section 5.6).

It is an important feature of the modelling of wood fuel supply from forests, either outside or within the EU27 region, that co-production of wood products might occur. Consequently, it was necessary for North Energy Associates to develop of a workbook representing the production of relevant wood products consisting of virgin (new) paper and card; medium density fibreboard (MDF); chipboard and panel board (particleboard); oriented strand board (OSB); wooden pallets; wooden fencing; structural timber consisting of wooden flooring and wooden window frames; and horticultural mulch from bark that is not used for fuel (see Section 5.7). Since such wood products comprise extra or marginal outputs, it was also necessary for North Energy Associates to include the production of counterfactuals to these wood products in this workbook. These counterfactuals consisted of recycled paper and card; blockwork (thermalite block external wall cladding); plasterboard partition walling; recycled plastic pallets; concrete fencing; concrete screed flooring; uPVC window frames; and horticultural mulch from arboricultural arisings (tree prunings). Additionally, because wood products and their counterfactuals must be disposed of at their lives, North Energy prepared a workbook representing a range for disposal options for wood products and their counterfactuals (see below).

The supply of solid biomass for energy use in the EU27 region is derived not only from forest wood but also agricultural biomass, energy crops and solid biowaste. In the VTT-TIAM model, agricultural biomass consists of wood chips and pellets derived from arboricultural arisings, and bales and pellets using straw recovered from cereal production. Hence, North Energy Associates developed workbooks for these sources of solid biomass. Additionally, Alterra calculated GHG emissions associated with changes in the carbon content of soils due to straw removal. Energy crops specified in the VTT-TIAM model covers all biomass derived from intentional cultivation. Consequently, this includes the production of wood chips and pellets from poplar and willow as short rotation coppice (SRC), and the production of bales and chips from miscanthus, reed canary grass and switchgrass (see Section 5.3). Solid biowaste was assumed to compromise the organic fraction of waste materials including municipal solid waste (MSW). Due to differences between these particular sources of solid biomass, North Energy Associates prepared separate workbooks for the supply and use of agricultural biomass (see Section 5.8), grass and woody energy crops (see Section 5.9), and solid biowaste (see below).

Alterra undertook evaluation of GHG emissions associated with the cultivation and harvesting of all energy crops in the EU27 region (see Section 5.3) which incorporated emissions factors for relevant agricultural inputs from the EFD. As well as willow, poplar, miscanthus, reed canary grass and switchgrass, Alterra's calculations also addressed the cultivation of crops for biofuel production, including barley, maize (corn), oilseed rape, sugar beet, sunflowers and wheat, and the cultivation of fodder maize (silage) for biogas production using anaerobic digestion. Additionally, Alterra determined GHG emissions from direct land use change for all energy crop production in the EU27 region. Since the evaluation of biofuel crops by Alterra was "up to the farm gate", North Energy Associates devised separate workbooks for all subsequent stages of biodiesel and bioethanol production and use, as well as the anaerobic digestion of fodder maize for biogas production (see Section 5.9). North Energy Associates also prepared workbooks for importing biodiesel and bioethanol into the EU27 region including the cultivation and harvesting of relevant crops grown outside the EU27 region (see Section 5.10). Since counterfactuals to animal feeds co-products from the production of biofuels had to be taken into account, a suitable workbook was developed by North Energy to represent their associated GHG emissions (see Section 5.11).

Various uses of wood are accommodated in the VTT-TIAM model. Prominent uses consist of the combustion of wood chips and pellets to generate heat, combined heat and power and electricity. It should be noted that such uses are based on wood, provided in suitable fuel form, from any source including forests within and outside the EU27 region, and within the EU27 region also including arboricultural arisings and energy crops such as poplar and willow. Other uses of wood envisaged in the VTT-TIAM model involve producing biofuels. These include the production and use of bioethanol from the lignocellulosic processing of wood chips; petrol blendstock (bio-oil) from fast pyrolysis of wood chips and hydro-treatment of pyrolysis oil; biokerosene from Fischer-Tropsch processing of wood chips; and bio-synthetic natural gas (bioSNG) from gasification of wood chips. Hence, North Energy Associates developed two separate workbooks representing the use of wood by combustion (see Section 5.12) and its conversion to liquid and gaseous biofuels (see Section 5.13).

The use of black liquor from the production of paper and card production within the EU27 region features in the VTT-TIAM model and, hence, it is necessary to account for its GHG combustion emissions (see Section 5.14). The generation of combined heat and power by the combustion of solid biowaste, and the production of bioethanol from the lignocellulosic processing of biowaste were represented in a workbook prepared by North Energy Associates (see Section 5.15). This workbook also addresses the counterfactual disposal of solid biowaste to landfill without or with energy recovery, and incineration without energy recovery. Another workbook developed by North Energy Associates reflected the disposal of wood products and their counterfactuals within and outside the EU27 region (see Section 5.16). This workbook includes the landfill disposal of inert (non-biogenic) wastes, which cannot breakdown into GHG emissions; the disposal of wood products to landfill without and with energy recovery; and the disposal of wood products to incineration without and with energy recovery. Finally, GHG emissions associated with the use of biogas for combined heat and power, and electricity generation; and grid injection with subsequent combustion were evaluated in another North Energy Associates workbook (see Section 5.17).

Table 5.1 Summary of pathways for evaluating indirect GHG emissions

General Pathways	Specific Coverage
Fossil and nuclear fuel, and electricity imports to EU27 region	Supply of hard coal, coke, crude oil, natural gas liquids, diesel, gasoline/petrol, heavy fuel oil, liquefied petroleum gas, natural gas and liquefied natural gas; supply of uranium; and supply of electricity.
Wood fuel imports to EU27 region	Supply and use of wood pellets from forests; co-production of related wood and their counterfactuals; and end-of-life disposal of wood products and their counterfactuals.
Wood fuel supply within EU27 region	Supply and use of wood chips and pellets from forests; co-production of related wood products; production of counterfactuals to wood products and their counterfactuals; and end-of-life disposal of wood products and their counterfactuals.
Agricultural biomass supply within EU27 region	Supply and use of wood chips and pellets from arboricultural arisings; and supply and use of straw bales and straw pellets.
Energy crop supply within EU27 region	Supply and use of biodiesel from oilseed rape and sunflowers; supply and use of bioethanol from barley, maize (corn), sugar beet and wheat; production of faba bean meal and potatoes as counterfactuals to animal feed co-products of biofuels; supply and use of bales and chips from miscanthus, reed canary grass and switchgrass; supply of wood chips and pellets from poplar and willow; and supply and use of fodder (silage) maize.
Biofuel imports to EU27 region	Supply and use of biodiesel from soy beans; supply and use of bioethanol from maize (corn), sugar cane and wheat; production of barley straw and faba bean meal as counterfactuals to animal feed co-products of biofuels; and supply and use of biokerosene from Fischer-Tropsch processing of wood.
Aggregated wood use within EU27 region	Use of wood chips and pellets (from any source) for generating heat, combined heat and power, and electricity.
Biofuel supply from wood within EU27 region	Supply and use of bioethanol from lignocellulosic processing of wood chips; supply and use of petrol blendstock (bio-oil) from fast pyrolysis of wood chips and hydrotreatment of pyrolysis oil; supply and use of biokerosene from Fischer-Tropsch processing of wood chips; supply and use of bio-synthetic natural gas (bioSNG) from gasification of wood chips.
Black liquor use within EU27 region	Combustion of black liquor from paper and card production from wood.
Solid biowaste use within EU27 region	Use of solid biowaste by incineration for combined heat and power generation; use of solid biowaste by lignocellulosic processing for bioethanol production and use; and counterfactual disposal of solid biowaste.
Biogas and waste gas use within EU27 region	Use of biogas for combined heat and power, and electricity generation; and use of biogas through grid injection and pipeline supply.

All relevant details of the evaluation of GHG emissions in the workbooks developed by North Energy Associates for this project are provided, along with references for sources of data and assumptions, to establish a suitable audit trail and to ensure adequate transparency. All these workbooks adopt a simplified and standardised layout for any given pathway to assist access to and understanding of the calculations, assumptions and sources of data. An example of this is presented in Figure 5.1. Before opening any pathway workbook, it is necessary to open the EFD so that relevant emissions factors can be accessed by the pathway workbook. Each chosen pathway is represented in a single worksheet in the relevant workbook. A brief descriptor for the pathway is given in Cell A1. The year selected in the EFD for values of emissions factors and subsequently used in the pathway worksheet is replicated in Cell D1.

The essential pathway stages and exchange of main inputs and outputs between these stages are represented, in the form of a vertical flow chart, in Columns B to D. Pathway stages are identified by elements with a white background and bold black borders. Exchanges of main inputs and outputs are contained in elements with a light yellow background and thin black borders. Descriptions of key parameters which influence subsequent GHG emissions are presented in Column B. Values for these key parameters are recorded in designated boxes in Column C. Brief notes explaining the values adopted for these parameters are contained in adjacent boxes in Column F. These notes include references which are documented in a separate worksheet in each workbook.

The choice of parameters specified in each pathway worksheet depends on their relative significance in the evaluation of associated GHG emissions. This was mainly based on existing experience of North Energy Associates in the evaluation of GHG emissions for the pathways under consideration. Additionally, the choice was guided by the likely influence of parameters in generating realistically-possible ranges of results. Many of the chosen parameters affect results through modelling relationships which are embedded in the pathway worksheets.

Subsequent results, as estimated contributions to GHG emissions, are displayed in Column H. The final result, which is the sum of all contributions to GHG emissions, is given toward the end of entries in Column H. At the top of Column H in Cell H1, the units relevant to the results are stated. These are in terms of kgCO_2-eq. per functional unit relevant to the pathway worksheet. The functional unit will depend on the nature of the pathway and the intended use of the results in subsequent analysis with the outputs of the VTT-TIAM model. Typically, the selected functional unit will consist of given amount of biomass feedstock which is provided at the start of a pathway or an amount of energy available at the end of a pathway, both often measured in MJ (10^6 joules) in keeping with the units that can be specified in the VTT-TIAM model (PJ; 10^{15} joules). In other instances, functional units consist of a given amount of material, such as oven dry (0% moisture content) tonnes of wood.

As indicated previously, the incorporation of key parameters into the pathway worksheets provides them with modelling capability. This is achieved by embedding relevant formulae in appropriate Cells which rely on these parameters, singly or in combination. The formulae are formulated with reference to specified parameters as well as particular values of data referred to in the notes which are derived from the cited references. Formulae are also used in relevant Cells to derive estimated contributions to associated GHG emissions. All formulae can also include emissions factors, specified by their unique cell names, from the EFD. In order to distinguish any Cell in a pathway worksheet that contains a formula, these are colour-coded with a rose background. Entries in such Cells should not be over-written. In contrast, the values in Cells with light blue backgrounds can either be changed by entering in different values or by selecting other choices from drop-down menus.

The functionality of the workbooks was devised so that each pathway worksheet could be used to produce a range of results, consisting of low and high values, which would reflect reasonable variations of estimated GHG emissions for a given pathway for a specified year and location either within or outside the EU27 region. The choice of values of parameters that generate low and high values in estimated total GHG emissions are again based on the judgment and experience of North Energy Associates. It should be noted that subsequent ranges are not intended to represent extreme low (absolute minimum) and extreme high (absolute maximum) values of results. Instead, they are intended to reflect typical variations that might be encountered under reasonably varying circumstances. These low and high values are used, in combination with the outputs of the VTT-TIAM, MITERRA and CARBINE models, to produce the range of final results from this project for each specified scenario.

Low and high values of results generated by the pathway workbooks are recorded in a separate summary worksheet in each workbook. Specific parameter values and choices used to produce these results are documented briefly in the summary worksheets so that a suitable audit trail is provided which allows results to be replicated and checked. Hence, summary worksheets contain a matrix of results with low and high values for the years 2010, 2020 and 2030.

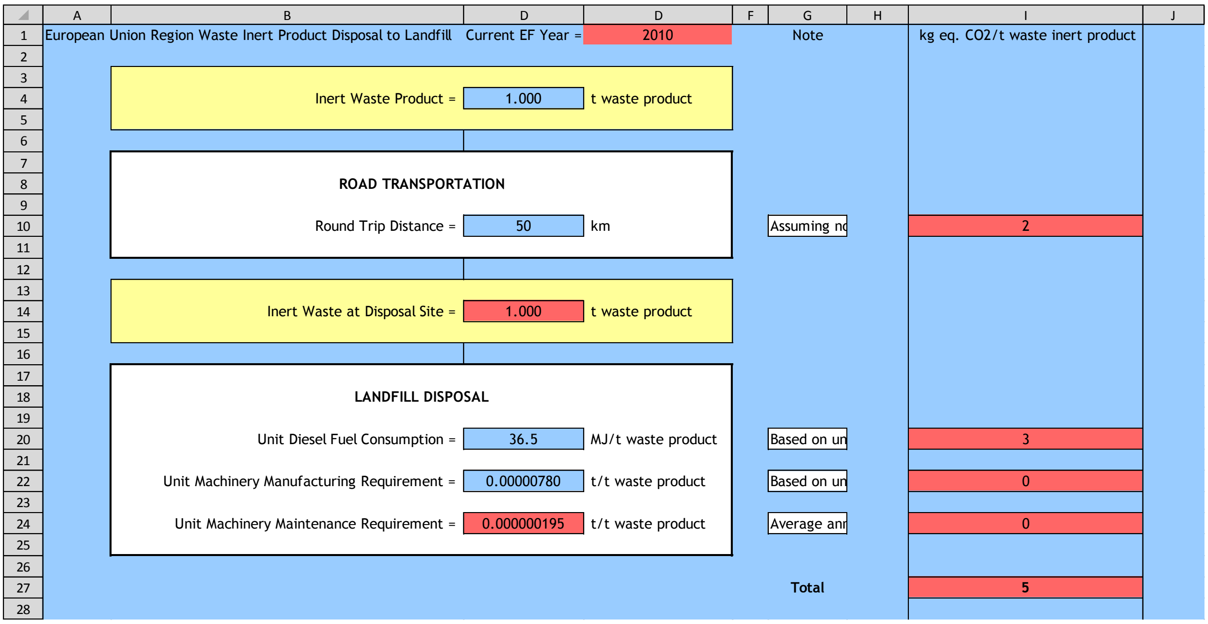

Figure 5.1. Example of pathway representation in a North Energy Associates workbook.

5.3. GHG emission factors for cultivation of energy crops

For Task 4, the MITERRA-Europe model was used to derive the farm-gate LCA based emissions factors for all energy crops (both annual and perennial crops). MITERRA-Europe, developed by Alterra, is an environmental assessment model, which calculates GHG (CO_2, CH_4 and N_2O) emissions, soil organic carbon stock changes and nitrogen emissions from agriculture on a deterministic and annual basis (Velthof *et al*., 2009; Lesschen *et al*., 2011). MITERRA-Europe covers the agriculture sector at different spatial scales, e.g. for Europe this consists of EU27 scale, Member State scale and NUTS2 scale. The model comprises about 40 crops, including five perennial energy crops (miscanthus, switchgrass, canary reed, poplar and willow). MITERRA-Europe calculates the input of fertilizer and manure based on crop demand, availability of livestock manure and national fertilizer statistics.

MITERRA-Europe was used to derive the GHG emission factors for cultivation of energy crops. This approach was preferred over a default emission factor from an emission database, as this approach is more detailed and takes account of the regional differences in emissions. The farm-gate LCA emission factors include the following emissions sources: N_2O soil emissions (direct + indirect), fertilizer production, diesel use, pesticide use, CO_2 from urea application and liming and CO_2 from organic soils. Calculation of GHG emissions are based on the IPCC 2006 guidelines. Further details on the calculation of the respective GHG emissions can be found in Lesschen *et al*. (2011) and Leip *et al*. (2014).

The LCA emissions factors for agricultural inputs were derived from the EF database from North Energy Associates. The database provides values for 2010, 2020 and 2030 (Table 5.2) and, for 2040 and 2050, the EFs from 2030 were used. As input data for 2010, the statistics from 2008 were used, whereas for the other years balanced fertilization was assumed to calculate the fertilizer inputs. Crop-specific GHG emissions were first calculated at NUTS2 level and later aggregated to EU level according to the amount of crops cultivated for bioenergy in each Member State. Figure 5.2 shows the amount of crops used for bioenergy for each scenario as derived from the VTT-TIAM results. The final total EF for crop cultivation was provided for the individual greenhouse gasses (i.e. CO_2, CH_4 and N_2O), in order to have the possibility to use other GWP values. Crop cultivation emissions factors were calculated for 2010, 2020, 2030, 2040 and 2050 and for each of the six scenarios.

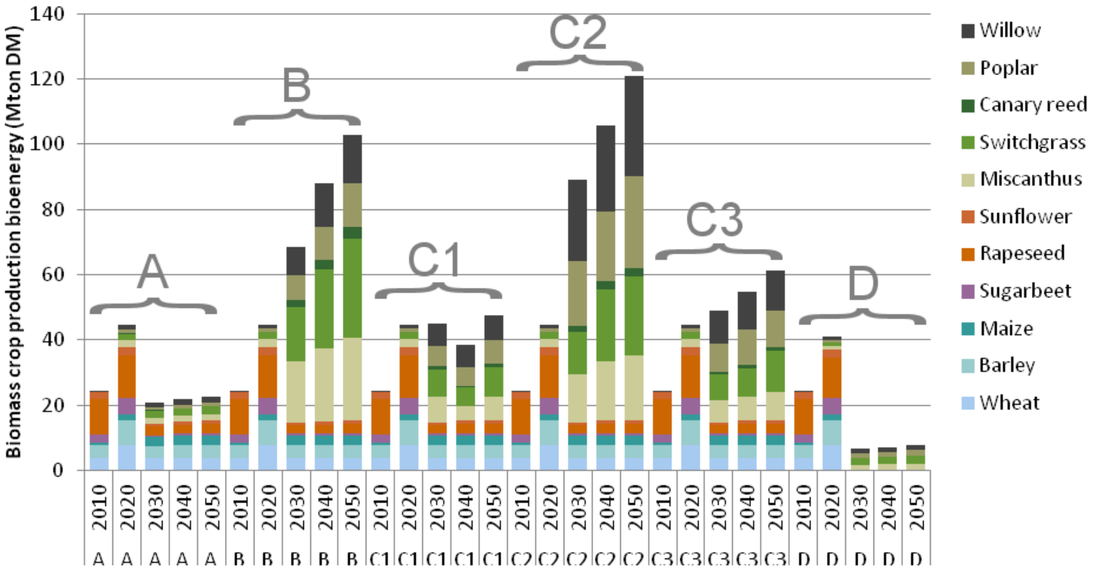

Figure 5.2. EU total biomass crop production for bioenergy for each scenario. (1 Mton DM = 1 odt).

Table 5.2 LCA emission factors from the NorthEnergy EF database for agricultural emission sources

Agricultural inputs	Year	CO_2	CH_4	N_2O	Unit
Pesticides	2010	10.68	0.0166	0.00175	kg $CO_2/CH_4/N_2O$ / kg a.i.
	2020	9.09	0.0138	0.00181	kg $CO_2/CH_4/N_2O$ / kg a.i.
	2030	8.04	0.0128	0.00176	kg $CO_2/CH_4/N_2O$ / kg a.i.
Diesel	2010	0.0822	0.0000121	0.0000288	kg $CO_2/CH_4/N_2O$ /MJ
	2020	0.0817	0.0000112	0.0000288	kg $CO_2/CH_4/N_2O$ /MJ
	2030	0.0814	0.0000102	0.0000287	kg $CO_2/CH_4/N_2O$ /MJ
Limestone	2010	0.037	0.0000401	0.00000168	kg $CO_2/CH_4/N_2O$ /kg $CaCO_3$
	2020	0.0274	0.000028	0.00000206	kg $CO_2/CH_4/N_2O$ /kg $CaCO_3$
	2030	0.0191	0.0000187	0.000002	kg $CO_2/CH_4/N_2O$ /kg $CaCO_3$

Table 5.2 (continued) LCA emission factors from the NorthEnergy EF database for agricultural emission sources

Agricultural inputs	Year	CO_2	CH_4	N_2O	Unit[1,2]
Ammonium Nitrate	2010	2.34	0.00621	0.0125	kg $CO_2/CH_4/N_2O$ /kg N
	2020	1.77	0.00497	0.0028	kg $CO_2/CH_4/N_2O$ /kg N
	2030	1.77	0.00497	0.0028	kg $CO_2/CH_4/N_2O$ /kg N
Urea	2010	1.39	0.0076	0	kg $CO_2/CH_4/N_2O$ /kg N
	2020	0.98	0.0066	0	kg $CO_2/CH_4/N_2O$ /kg N
	2030	0.98	0.0066	0	kg $CO_2/CH_4/N_2O$ /kg N
Triple Super phosphate	2010	0.505	0.000508	0.0000248	kg $CO_2/CH_4/N_2O$ /kg P_2O_5
	2020	0.464	0.000477	0.0000276	kg $CO_2/CH_4/N_2O$ /kg P_2O_5
	2030	0.432	0.000425	0.0000273	kg $CO_2/CH_4/N_2O$ /kg P_2O_5
Muriate Potash	2010	0.915	0.00182	0.0000513	kg $CO_2/CH_4/N_2O$ /kg K_2O
	2020	0.893	0.00184	0.000052	kg $CO_2/CH_4/N_2O$ /kg K_2O
	2030	0.88	0.00178	0.000052	kg $CO_2/CH_4/N_2O$ /kg K_2O

Notes to Table 5.2:

1 For brevity, units are shown in compressed form. For example, for ammonium nitrate, the units for the CH_4 emissions factor are kg CH_4/kg N, or kg CH_4 kg N^{-1}.

2 References should be made to the definitions of kg a.i. and "kg x" in the Glossary.

Figure 5.3 shows the final EU-27 emission factors for the respective energy crops expressed in kg CO_2-eq. per odt. Biodiesel crops (rapeseed and sunflower) have a much higher GHG emission per odt (about 950 kg CO_2-eq./odt) compared to the bioethanol crops, i.e. wheat, barley, maize and sugarbeet (about 350 kg CO_2-eq./odt), while the perennial energy crops have even a much lower GHG emission of about 100 kg CO_2-eq./odt. N_2O soil emissions are the main GHG source with a contribution of more than 50% for the annual crops, and about 35% for the perennial crops. Fertilizer production, diesel use and organic soils are other significant GHG sources.

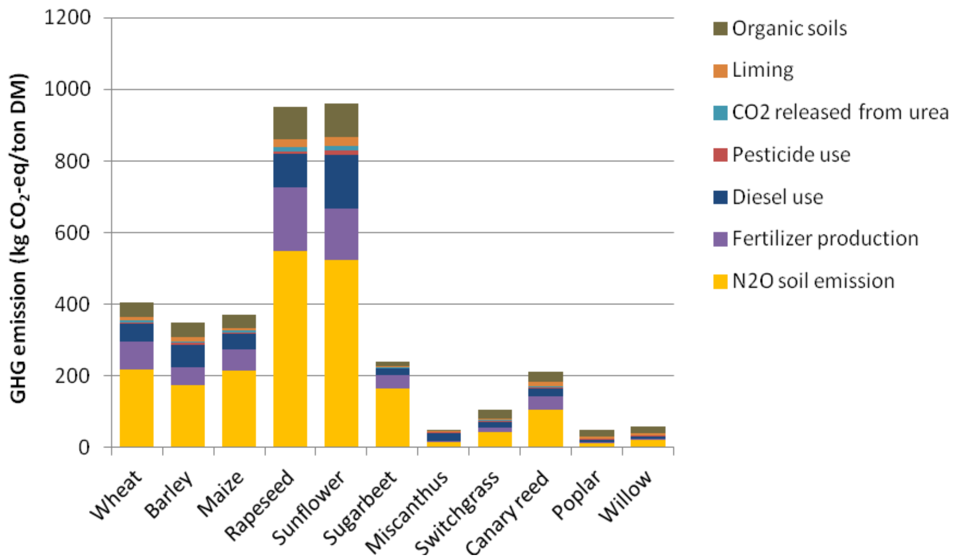

Figure 5.3. Composition of EU average GHG emission factors for energy crops (data for 2030 of scenario B).

5.4. Indirect GHG emissions associated with forest operations

Indirect GHG emissions associated with forest operations were calculated using the CARBINE model. An example of such calculations is given in Appendix 8.

5.5. Indirect GHG emissions associated with fossil and nuclear fuel, and electricity imports

Indirect GHG emissions associated with the import of fossil and nuclear fuels, and electricity into the EU27 region are intended to cover all sources of GHG emissions located outside this region. Hence, these emissions include CH_4 emissions leakages to the atmosphere from coal mining, and crude oil and natural gas extraction, processing and transportation, by pipeline and ship, up to the borders of the EU27 region. The basic emissions factors used to estimate these indirect GHG emissions are summarised in the workbook “EC BCI Non-Biomass Imports v04.xlsx”. All the emissions factors recorded in this workbook were derived from the GEMIS database. Subsequent emissions factors for use in the analysis and generation of final results on total GHG emissions for the EU27 region are presented in Table 5.3.

Emissions factors for hard coal imports, specified in the VTT-TIAM model, were equated to GEMIS data for EU coal import mixes for 2010, 2020 and 2030. Emissions factors for coke imports were derived from production data, reflecting Germany in 2010, 2020 and 2030, and average emissions data for transport from Russia and the USA as currently prominent suppliers of the EU. Emissions factors for crude oil and natural gas liquids imports were equated to GEMIS data for EU crude oil import mixes for 2010, 2020 and 2030. Emissions factors for petroleum products, specified in the VTT-TIAM model as diesel, gasoline, heavy fuel oil, liquefied petroleum gas (LPG) and naphtha, were estimated using GEMIS data for heavy oil fuel production by Organisation for Petroleum

Exporting Countries (OPEC) in 2010, 2020 and 2030, and high fuel oil production in Russia and the USA in 2010, 2020 and 2030, plus emissions associated with petroleum product transportation between these countries and the EU. These countries were chosen as currently prominent sources of petroleum product imports to the EU. Emissions factors for natural gas and liquefied natural gas imports to the EU27 were equated to GEMIS data for EU natural gas import mixes in 2010, 2020 and 2030. Limited data were available on the production of fuel imports for use in nuclear power. Hence, approximate emissions factors were formed from average of GEMIS data for uranium production in Africa, Canada, Russia and the USA in 2010, plus emissions associated with transportation between these countries and the EU. Similarly, no detailed data were available on the GHG emissions associated with the current and possible future import of electricity into the EU27 region. Consequently, emissions factors were approximated to GEMIS data for grid electricity in Russia in 2010, 2020 and 2030.

It will be apparent that approximations were used for emissions factors for EU27 region imports of coke, petroleum products, uranium and electricity. However, it is known from subsequent analysis and preparation of results that these imports make relatively small contributions to total GHG emissions in the EU27 region under the Scenarios considered here. More significant contributions are possible from EU27 region imports of hard coal, crude oil and natural gas liquids, and natural gas, and more specific emissions factors for 2010, 2020 and 2030 are used to determine their associated indirect GHG emissions. It is also important to note that these emissions factors for fossil fuel imports only address their indirect GHG emissions, as direct emissions from their combustion in the EU27 region are represented in the VTT-TIAM model.

Table 5.3 Emissions factors for fossil and nuclear fuel, and electricity imports into EU27 region

EU27 Region Import	Emissions Factor ($kgCO_2$-eq. MJ^{-1})		
	2010	**2020**	**2030**
Hard Coal (mix)	0.0118	0.0128	0.0092
Oven Coke	0.0161	0.0139	0.0110
Crude Oil and Natural Gas Liquids	0.00521	0.00470	0.00459
Petroleum Products	0.0190	0.0183	0.0177
Natural Gas (mix)	0.00773	0.00764	0.00839
Uranium	0.000532	0.000532	0.000532
Electricity	0.188	0.125	0.108

5.6. GHG emissions associated with wood fuel supply

The derivation of GHG emissions associated with the supply of wood fuel outside and within the EU27 region is provided by calculations contained in the workbook, “EC BCI Wood Fuel Supply v06.xlsx”. This workbook represents 6 pathways for the production of wood fuel. These pathways consist of wood pellet supply from Brazil, representing the LAM region, from Russia, representing the CIS region, from the USA and from Canada, and wood chip and pellet supply in the EU27 region.

For consistency with the results from the CARBINE model, with which subsequent emissions factors for wood fuel supply are used, the starting point of each pathway is wood at the roadside in the forest. It should be noted that all GHG emissions, including those associated with forest management, harvesting and extraction, are addressed separately by the CARBINE model. The end point of all imported wood pellet pathways is the receiving port at the borders of the EU27 region. The end points of pathways for wood fuel produced within the EU27 region are wood chip and pellet distribution centres. All GHG emissions associated with the distribution and subsequent use of these wood fuels are addressed separately in relevant workbooks (see Sections 5.12 and 5.13).

Along all these pathways, losses of wood are possible and it has been assumed that all such losses will, ultimately, lead to combustion of wood waste. In a further aspect of consistency with the CARBINE model, the evaluation of any such combustion of wood includes CO_2 emissions from biogenic carbon content. This is because the CARBINE model accounts for the sequestration of carbon in wood during tree growth in the forest. Additionally, CO_2 emissions from the eventual combustion of wood fuel supply from outside and within the EU27 region is represented separately in the analysis and preparation of results. However, such emissions are not represented in this manner for all other (generally agricultural) sources of wood in the EU27 region (see Sections 5.8 and 5.9) as their supply does not include any CO_2 sequestration as part of the modelling in this project.

The emissions factors for wood fuel supply in connection with generating final results for total GHG emissions for the EU27 region with outputs from the CARBINE model are summarised in Table 5.4. Low and high values are provided to represent the reasonably expected range of these emissions factors. The main factors which influence these emissions factors consist of the round trip distance for transporting wood from the roadside in the forest to the chipping and/or pelletising plant, the type of fuel used for drying wood (wood itself or relevant fossil fuel), and the modes of transport and distances involved in supplying wood pellets from their countries of origin to the borders of the EU27 region. The range of values for wood fuel supply from forests within the EU27 region also takes into account the use of wood chips (for low values) or wood pellets (for high values).

Table 5.4 Emissions factors for wood fuel supply from outside and within EU27 region

Wood Fuel by Source*	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} wood at roadside in forest)		
		2010	2020	2030
Wood Pellets from LAM	Low	0.0069	0.0065	0.0062
	High	0.0294	0.0290	0.0287
Wood Pellets from CIS	Low	0.0055	0.0040	0.0036
	High	0.0269	0.0248	0.0241
Wood Pellets from USA	Low	0.0066	0.0061	0.0059
	High	0.0310	0.0307	0.0306
Wood Pellets from CAN	Low	0.0037	0.0061	0.0045
	High	0.0287	0.0325	0.0318
Wood Chips/Pellets from EU27	Low	0.0007	0.0006	0.0006
	High	0.0205	0.0198	0.0188

*See Table 1.1, Section 1.4, for definitions of regions

5.7. GHG emissions associated with wood products and counterfactuals

The estimation of GHG emissions associated with the production of material wood products from wood in forests outside and within the EU27 region is undertaken in the workbook, "EC BCI Wood Products and Counterfactuals v03.xlsx". This workbook represents pathways for the production of virgin paper and card, MDF, particleboard, OSB, structural timber, wooden pallets, wooden fencing and horticultural mulch from bark. Subsequent emissions factors for these wood products used with outputs from the CARBINE model in analysis and generation of results on total GHG emissions for the EU27 region are summarised in Tables 5.5 to 5.12. These emissions factors, as ranges between low and high values, are given for Brazil representing the LAM region, Russia representing the CIS region, the USA, Canada and the EU27 region.

It should be noted that the starting point for all the pathways involved in the production of these material wood products is wood at the roadside in the forest. All GHG emissions prior to this point are accounted for separately in the CARBINE model. The end point for all the pathways is wood products delivered to end users. For consistency with the incorporation of sequestered carbon in the outputs from the CARBINE model, any CO_2 emissions from the combustion of waste wood arising from losses is included in the evaluation performed in this workbook. Additionally, in order for their compatible use with outputs from the CARBINE model, emissions factors for wood products are expressed in terms of oven-dry (od) t of wood at the roadside in the forest required in the production of relevant wood products.

Table 5.5 presents emissions factors for virgin paper and card production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values are the round trip distance for transporting wood from the roadside in the forest to the pulpmill, and the choice of source of heat and electricity used in the pulpmill. In particular, the low value was based on the use of waste wood in a CHP unit for the pulpmill and the high value was based on a fuel oil-fired boiler with imported grid electricity. This choice of sources of heat and electricity in the pulpmill affects the amount of paper and card derived from wood at the roadside in the forest which ranges from 0.548 to 0.600 t odt^{-1}. This assumes a moisture content of 3% for finished paper and card which incorporates coatings.

Table 5.5 Emissions factors for production of virgin paper and card outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Virgin Paper and Card in LAM Region	Low	1448	1471	1480
	High	1924	1901	1875
Virgin Paper and Card in CIS Region	Low	1450	1473	1481
	High	2028	1900	1863
Virgin Paper and Card in USA	Low	1447	1470	1479
	High	1998	1964	1943
Virgin Paper and Card in Canada	Low	1447	1470	1479
	High	1696	1909	1762
Virgin Paper and Card in EU27 Region	Low	1448	1471	1480
	High	1881	1839	1813

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.6 shows the emissions factors for MDF production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 1.12 t of MDF are derived from each odt of wood at the roadside in the forest. This assumes the incorporation of recycled waste wood, resins, waxes and other chemicals, resulting in a wood content of 89% in the MDF. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting all inputs, including wood from the roadside in the forest, to the MDF plant, and the round trip distance for transporting MDF to end users.

Table 5.6 Emissions factors for production of MDF outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	**2020**	**2030**
MDF in LAM Region	Low	2095	2068	2014
	High	2185	2157	2130
MDF in CIS Region	Low	2149	2010	1968
	High	2237	2097	2055
MDF in USA	Low	2093	2053	2030
	High	2176	2137	2114
MDF in Canada	Low	1843	2066	1909
	High	1926	2153	1999
MDF in EU27 Region	Low	1975	1930	1903
	High	2060	2014	1987

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.7 presents the emissions factors for particleboard (chipboard and other panel board) production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 3.91 t of particleboard are derived from each odt of wood at the roadside in the forest. This assumes the incorporation of recycled wood, resins, waxes and other chemicals, resulting in a wood content of 90% for the particleboard. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting all inputs, including wood from the roadside in the forest, to the particleboard plant, and the round trip distance for transporting particleboard to end users.

Table 5.8 summarises the emissions factors for OSB production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 0.776 t of OSB are derived from each odt of wood at the roadside in the forest. This assumes the incorporation of resins, waxes and other wood products, resulting in a wood content of 95% for OSB. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting all inputs, including wood from the roadside in the forest to the OSB plant, and the round trip distance for transporting OSB to end users.

Table 5.7 Emissions factors for production of particleboard outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Particleboard in LAM Region	Low	2306	2272	2237
	High	2492	2459	2423
Particleboard in CIS Region	Low	2487	2305	2246
	High	2668	2484	2424
Particleboard in USA	Low	2382	2332	2299
	High	2552	2503	2471
Particleboard in Canada	Low	2211	2536	2352
	High	2382	2715	2537
Particleboard in EU27 Region	Low	2235	2179	2146
	High	2405	2347	2313

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.8 Emissions factors for production of OSB outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
OSB in LAM Region	Low	935	925	914
	High	1028	1017	1007
OSB in CIS Region	Low	955	900	882
	High	1046	990	973
OSB in USA	Low	933	917	908
	High	1019	1005	996
OSB in Canada	Low	832	923	860
	High	920	1013	954
OSB in EU27 Region	Low	886	869	858
	High	975	957	946

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.9 summarises the emissions factors for structural timber production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting wood from the roadside in the forest to the sawmill, and the round trip distance for transporting structural timber to end users, and the choice of source of heat and electricity used in the sawmill. In particular, the low value was based on the use of waste wood in a CHP unit for the sawmill and the high value was based on a fuel oil-fired boiler with imported grid electricity. This choice of sources of heat and electricity in the sawmill affects the amount of structural derived from wood at the roadside in the forest which ranges from 0.830 to 0.970 t odt^{-1}. The moisture content of structural timber is assumed to be 15%.

Table 5.9 Emissions factors for production of structural timber outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Structural Timber in LAM Region	Low	403	404	404
	High	523	516	510
Structural Timber in CIS Region	Low	403	403	403
	High	533	497	487
Structural Timber in USA	Low	403	403	403
	High	526	515	509
Structural Timber in Canada	Low	402	403	404
	High	459	518	481
Structural Timber in EU27 Region	Low	403	403	403
	High	494	481	474

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.10 summarises the emissions factors for wooden pallet production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 1.88 t of wooden pallets are derived from each odt of wood at the roadside in the forest. This assumes a moisture content of 10% for wooden pallets and the incorporation of steel nails or other fixings. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting wood from the roadside in the forest to the wooden pallet plant, and the round trip distance for transporting wooden pallets to end users.

Table 5.11 summarises the emissions factors for wooden fencing production in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 1.99 t of wooden panel fencing are derived from each odt of wood at the roadside in the forest. This assumes a moisture content of 25% for wooden fencing panels and the incorporation of steel nails or other fixings. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting wood from the roadside in the forest to the wooden fencing plant, and the round trip distance for transporting wooden fencing to end users.

Table 5.10 Emissions factors for production of wooden pallets outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor (kgCO_2-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Wooden Pallets in LAM Region	Low	527	534	534
	High	625	632	632
Wooden Pallets in CIS Region	Low	526	534	533
	High	623	630	628
Wooden Pallets in USA	Low	526	534	533
	High	617	625	625
Wooden Pallets in Canada	Low	526	534	534
	High	618	629	632
Wooden Pallets in EU27 Region	Low	526	534	533
	High	619	626	625

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.11 Emissions factors for production of wooden fencing outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor (kgCO_2-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Wooden Fencing in LAM Region	Low	202	211	210
	High	256	266	265
Wooden Fencing in CIS Region	Low	202	211	210
	High	255	263	262
Wooden Fencing in USA	Low	201	210	209
	High	251	260	260
Wooden Fencing in Canada	Low	201	211	210
	High	251	263	264
Wooden Fencing in EU27 Region	Low	201	210	209
	High	251	260	258

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.12 summarises the emissions factors for production of horticultural mulch from bark in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The pathways described in the workbook incorporate the assumption that 1.87 t of horticultural mulch are derived from each odt of bark at the roadside in the forest. This assumes a moisture content for horticultural mulch from bark of 50%. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting bark from the roadside in the forest to the horticultural mulch plant, and the round trip distance for transporting horticultural mulch to end users.

Table 5.12 Emissions factors for production of horticultural mulch from bark outside and within EU27 region

Wood Product by Source*	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} wood input from roadside in forest)		
		2010	2020	2030
Horticultural Mulch from Bark in LAM Region	Low	133	133	132
	High	169	169	168
Horticultural Mulch from Bark in CIS Region	Low	133	131	131
	High	168	166	165
Horticultural Mulch from Bark in USA	Low	132	132	132
	High	165	165	165
Horticultural Mulch from Bark in Canada	Low	129	132	131
	High	162	167	167
Horticultural Mulch from Bark in EU27 Region	Low	131	130	130
	High	163	163	162

*See Table 1.1, Section 1.4, for definitions of regions

The production of each of these wood products has the potential to displace the production of possible counterfactuals, and vice versa. A list of possible counterfactuals was prepared during this project and this is reproduced in Table 5.13. The counterfactuals were based on physical alternatives to wood product applications. This involved specifying equivalent functions for wood product applications and their counterfactuals. The equivalent functions consisted of 1 t of finished paper and card; 1 m^2 surface area of partition wall; 1 m^2 surface area of external wall cladding; 1 standard UK pallet; 1 m^2 surface area of fencing; 1 m^2 surface area of flooring; 1.2 m square window frame and 1 t of horticultural mulch. Values of equivalence, in terms of t of counterfactual per unit odt of timber at the roadside in the forest for given wood products, were estimated from these equivalent functions. Calculations of values of equivalence, including the assumptions on which these are based, are recorded in the workbook, "EC BCI Wood Products and Counterfactuals v03.xlsx", which also includes the counterfactual pathways and their associated GHG emissions. This covers the production of recycled paper and card; a blockwork external wall; recycled plastic pallets; concrete panel fencing; concrete screed flooring; and horticultural mulch from arboricultural arisings in the regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. Emissions factors for plasterboard of 289 $kgCO_2$-eq. t^{-1} and for uPVC window frames of 1,200 $kgCO_2$-eq. t^{-1} (for all regions and years) were obtained from the EFD.

Table 5.13 Wood products, their counterfactuals and estimated equivalence

Wood Product Application	Counterfactual	Equivalence (t counterfactual per odt timber at roadside for wood product application)
Virgin Paper and Card	Recycled Paper and Card	0.600
MDF Partition Wall	Plasterboard Partition Wall	0.769
Particleboard External Wall Cladding	Blockwork External Wall Cladding	13.7
OSB External Wall Cladding	Blockwork External Wall Cladding	2.77
Wooden Pallets	Recycled Plastic Pallets	2.35
Wooden Fencing	Concrete Fencing	21.8
Structural Timber for Flooring	Concrete Screed Flooring	16.1
Structural Timber for Window Frame	uPVC Window Frame	0.479
Horticultural Mulch from Bark	Horticultural Mulch from Arboricultural Arisings	1.87

Table 5.14 summarises the emissions factors for production of recycled paper and card in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting all inputs, including recovered paper and card to the paper mill; the choice of producing cardboard and packing paper, or lightweight coated/super-calendered paper; the choice of using a natural gas-fired CHP unit or a fuel oil-fired boiler and imported grid electricity in the paper mill; and the round trip distance for transporting recycled paper and card to end users.

Table 5.14 Emissions factors for production of recycled paper and card outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor ($kgCO_2$-eq. t^{-1})		
		2010	2020	2030
Recycled Paper and Card in LAM Region	Low	901	914	915
	High	1169	1178	1177
Recycled Paper and Card in CIS Region	Low	982	987	974
	High	1161	1136	1149
Recycled Paper and Card in USA	Low	855	865	860
	High	1113	1121	1120
Recycled Paper and Card in Canada	Low	854	865	860
	High	1141	1177	1165
Recycled Paper and Card in EU27 Region	Low	896	913	920
	High	1084	1090	1085

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.15 summarises the emissions factors for production of blockwork external wall cladding in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. Blockwork external wall cladding consists of thermalite blocks with mortar composed of sand and cement. The main factor that influences the range of emissions factors from the low to high values was the round trip distance for all materials for the blockwork external wall cladding to end users.

Table 5.15 Emissions factors for production of blockwork external wall cladding outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor (kgCO_2-eq. t^{-1})		
		2010	2020	2030
Blockwork External Wall Cladding in LAM Region	Low	256	254	253
	High	275	273	272
Blockwork External Wall Cladding in CIS Region	Low	255	254	253
	High	274	272	271
Blockwork External Wall Cladding in USA	Low	255	254	253
	High	272	271	270
Blockwork External Wall Cladding in Canada	Low	255	254	253
	High	273	272	272
Blockwork External Wall Cladding in EU27 Region	Low	255	254	253
	High	272	270	269

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.16 summarises the emissions factors for production of recycled plastic pallets in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for delivering high density polyethylene (HDPE) pellets to the pallet manufacturing plant and the round trip distance for transporting recycled plastic pallets to end users.

Table 5.16 Emissions factors for production of recycled plastic pallets outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor (kgCO_2-eq. t^{-1})		
		2010	2020	2030
Recycled Plastic Pallets in LAM Region	Low	13.6	13.6	13.6
	High	72.6	72.6	72.6
Recycled Plastic Pallets in CIS Region	Low	13.4	13.4	13.3
	High	70.1	69.2	68.7
Recycled Plastic Pallets in USA	Low	13.1	13.1	13.1
	High	65.8	66.3	66.7
Recycled Plastic Pallets in Canada	Low	13.1	13.4	13.5
	High	66.4	69.2	71.5
Recycled Plastic Pallets in EU27 Region	Low	12.9	12.9	12.9
	High	64.1	63.8	63.6

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.17 summarises the emissions factors for production of concrete panel fencing in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for delivering cement, sand and reinforcing bars to the concrete fencing manufacturing plant and the round trip distance for transporting concrete panel fencing components to end users.

Table 5.17 Emissions factors for production of concrete panel fencing outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor ($kgCO_2$-eq. t^{-1})		
		2010	2020	2030
Concrete Panel Fencing in LAM Region	Low	31.2	31.2	31.1
	High	48.2	48.2	48.1
Concrete Panel Fencing in CIS Region	Low	31.1	31.0	30.9
	High	47.4	47.1	46.8
Concrete Panel Fencing in USA	Low	30.8	30.8	30.7
	High	46.0	46.1	46.2
Concrete Panel Fencing in Canada	Low	30.8	30.9	31.1
	High	46.2	47.0	47.8
Concrete Panel Fencing in EU27 Region	Low	30.7	30.6	30.5
	High	45.4	45.3	45.2

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.18 summarises the emissions factors for production of concrete screed flooring in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factor that influences the range of emissions factors from the low to high values was the round trip distance for transporting cement and sand for concrete screed flooring to end users.

Table 5.18 Emissions factors for production of concrete screed flooring outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor ($kgCO_2$-eq. t^{-1})		
		2010	2020	2030
Concrete Screed Flooring in LAM Region	Low	187	181	177
	High	206	200	196
Concrete Screed Flooring in CIS Region	Low	187	181	176
	High	205	199	194
Concrete Screed Flooring in USA	Low	186	180	176
	High	204	198	194
Concrete Screed Flooring in Canada	Low	186	181	177
	High	204	199	195
Concrete Screed Flooring in EU27 Region	Low	186	180	176
	High	203	197	193

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.19 summarises the emissions factors for production of horticultural mulch from arboricultural arisings in regions relevant to the VTT-TIAM model for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting arboricultural arisings to the chipping plant and the round trip distance for transporting horticultural mulch to end users.

Table 5.19 Emissions factors for production of horticultural mulch from arboricultural arisings outside and within EU27 region

Wood Product Counterfactual by Source*	Value	Emissions Factor ($kgCO_2$-eq. t^{-1})		
		2010	2020	2030
Horticultural Mulch from Arboricultural Arisings in LAM Region	Low	7.05	6.82	6.62
	High	29.0	28.8	28.6
Horticultural Mulch from Arboricultural Arisings in CIS Region	Low	7.24	6.21	5.91
	High	28.6	27.3	26.9
Horticultural Mulch from Arboricultural Arisings in USA	Low	6.90	6.60	6.45
	High	26.9	26.8	26.8
Horticultural Mulch from Arboricultural Arisings in Canada	Low	5.14	6.79	5.76
	High	25.4	27.9	27.6
Horticultural Mulch from Arboricultural Arisings in EU27 Region	Low	5.99	5.61	5.40
	High	26.0	25.4	25.1

*See Table 1.1, Section 1.4, for definitions of regions

In addition to differences in emissions factors for material wood products and their counterfactuals, there are potential differences between their assumed lifetimes which would affect the timing of any GHG emissions associated with their eventual end-of-life disposal (see Section 5.16). The assumed values of average lifetimes for wood products and their counterfactuals are given in Tables 5.20 and 5.21, respectively. It should be noted that, although these values of lifetimes are subsequently adopted in the analysis and preparation of results from this project, it is possible to vary these values.

Table 5.20 Assumed values of average lifetimes for material wood products

Product	Average Lifetime (years)
Virgin Paper and Card (finished)	1
MDF Partition Wall	50
Particleboard and OSB External Wall Cladding	50
Wooden Pallet	2
Wooden Panel Fencing	15
Structural Timber for Flooring	60
Structural Timber for Window Frame	60
Horticultural Mulch from Bark	2

Table 5.21 Assumed values of average lifetimes for counterfactuals to material wood products

Product	Average Lifetime (years)
Recycled Paper and Card (finished)	1
Plasterboard Partition Wall	50
Blockwork External Wall Cladding	100
Recycled Plastic Pallet	8
Concrete Panel Fencing	45
Concrete Screed Flooring	100
uPVC Window Frame	100
Horticultural Mulch from Arboricultural Arisings	2

5.8. GHG emissions associated with EU27 agricultural biomass production

Agricultural biomass in the VTT-TIAM model consists of wood recovered from arboricultural operations and straw recovered after cereal crop harvesting in the EU27 region. The GHG emissions associated with the provision of fuels from these particular sources are evaluated in the workbook, "EC BCI Agricultural Biomass v05.xlsx". The pathways for arboricultural arisings represent the provision of wood chips and pellets in the EU27 region. However, the use of these wood chips and pellets is not included in this particular workbook. This is because these fuels are combined together with all other wood fuels in the VTT-TIAM model. Hence, GHG emissions associated with the use of all wood fuels are reflected in another, separate workbook (see Section 5.12).

The arboricultural arisings pathways in the workbook, "EC BCI Aggregated Biomass v05.xlsx", include road transportation of wood chips from the original site of operations, followed by drying and storage, and, for wood pellets, subsequent milling and pelletising. Since carbon sequestration during original tree growth is not taken into account for this particular source of wood fuels, CO_2 emissions from the combustion of wood losses in this pathway are not evaluated although CH_4 and N_2O emissions are included. The exclusion of such CO_2 emissions contrasts with their inclusion in the production and use of wood fuels from forests, which are addressed by the CARBINE model.

The relevant pathways for the provision of fuels from straw represent the production of straw bales and pellets. Both these pathways commence with the baling of cut straw in fields. GHG emissions associated with subsequent extra fertiliser applications due to straw removal are taken into account along with avoided GHG emissions from straw incorporation. It should be noted that avoided CO_2 emissions resulting from soil organic carbon changes due to straw incorporation were evaluated separately by Alterra (see Section 6.2). Other sources of GHG emissions for straw fuel pathways consist of straw bale loading, carting and storage with natural or artificial drying. Dried straw bales are then transported to end users or processed by milling and pelletising into straw pellets which are transported to end users. The combustion of straw bales and pellets in commercial/industrial-scale heating plants is included in the pathways as well as the road transportation and disposal of ash to landfill.

Table 5.22 summaries the emissions factors for the provision of wood fuel from arboricultural arisings, and the production and use of straw fuel within the EU27 region for 2010, 2020 and 2030. The main factors that influence the range of emissions factors from the low to high values were the round trip distance for transporting wood chips from arboricultural arisings, and the provision of either wood chips dried using wood as fuel or wood pellets with drying provided by fuel oil. In the case of straw fuel, the main factors that influence the range of emissions factors from the low to high values are the round trip transport distance of straw bale transportation to drying and storage, the choice of natural or artificial drying, the round trip distance for transporting straw bales or pellets to end users, and the round trip distance for transporting ash for disposal. For both wood and straw fuels, emissions factors are provided in terms of the amount of energy, in MJ, available at their original sources for consistency with the VTT-TIAM model.

Table 5.22 Emissions factors for provision of wood fuels from arboricultural arisings, and from the production and use of straw fuels within EU27 region

Agricultural Biomass	Value	Emissions Factor (kgCO_2-eq. MJ^{-1})		
		2010	**2020**	**2030**
Wood Fuel from Arboricultural Arisings in EU27 Region	Low	0.0005	0.0005	0.0005
	High	0.0169	0.0166	0.0159
Straw Fuel Production and Use in EU27 Region	Low	0.0063	0.0063	0.0062
	High	0.0137	0.0131	0.0125

5.9. GHG emissions associated with EU27 energy crop processing

As explained elsewhere (see Section 5.3), GHG emissions associated with the cultivation and harvesting of energy crops, consisting of oilseed rape and sunflowers for biodiesel production; barley, maize (corn), sugar beet and wheat for bioethanol production; miscanthus, reed canary grass and switchgrass; poplar and willow; and fodder maize for AD processing, in the EU27 region were evaluated by Alterra using the MITERRA-Europe model. Hence, it was necessary for all subsequent GHG emissions for these energy crops "beyond the farm gate" to be estimated separately. This was undertaken by North Energy Associates and calculations are documented in 5 separate workbooks: "EC BCI Biodiesel Production EU v05.xlsx", "EC BCI Bioethanol Production EU v05.xlsx", "EC BCI Crops Grass v04.xlsx", "EC BCI Crops Wood v03.xlsx", and "EC BCI Fodder Maize AD v02.xlsx".

Table 5.23 summarises the emissions factors for the production and use of biodiesel from oilseed rape and sunflowers in the EU27 region for 2010, 2020 and 2030. The pathways in the workbook, "EC BCI Biodiesel Production EU v05.xlsx", consist of road transportation of relevant crops to the biodiesel plant, conversion to biodiesel by extraction, refining and esterification, transportation of biodiesel via depots to filling stations, and subsequent combustion of biodiesel by end users in vehicles. These calculations take into consideration the effects of possible surplus electricity from a CHP unit in the biodiesel plant, by means of avoided GHG emissions from displaced grid electricity, and the co-production of oilseed rape meal and sunflower meal as animal feeds. This required the application of emissions factors for animal feed counterfactuals which are addressed elsewhere (see Section 5.11). It should be noted that the emissions factors given in Table 5.23 are per odt of energy crop provided "at the farm gate", for consistency with the approach adopted by Alterra for energy crop production.

Table 5.23 Emissions factors for processing of energy crops for biodiesel production and use within EU27 region

Energy Crop	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} energy crop)		
		2010	2020	2030
Oilseed Rape for Biodiesel Production and Use in EU27 Region	Low	-158	-143	-133
	High	143	138	133
Sunflowers for Biodiesel Production and Use in EU27 Region	Low	-178	-157	-143
	High	200	195	190

The main factors that influence the range of emissions factors from the low to high values are the round trip distance for road transportation of energy crops to the biodiesel plant, the choice of energy source (natural gas-fired CHP or coal-fired boiler with grid electricity) in the biodiesel plant, the choice of animal feed counterfactual emissions factor, the round trip distance and mode of transportation of biodiesel from the plant to the depot, and the round trip road transport distance for biodiesel from the depot to the filling station. As seen in Table 5.23, application of an avoided emissions factor for surplus electricity from the CHP unit in the biodiesel plant combined with a high emissions factor for the animal feed counterfactual results in negative emissions factors for biodiesel production and use. It should be noted, however, that this can be counter-balanced by GHG emissions associated with energy crop production, as addressed separately by Alterra.

Table 5.24 summarises the emissions factors for the production and use of bioethanol from barley, maize (corn), sugar beet and wheat in the EU27 region for 2010, 2020 and 2030. The pathways in the workbook, "EC BCI Bioethanol Production v05.xlsx", consist of road transportation of relevant crops to the bioethanol plant, conversion to bioethanol by fermentation, transportation of bioethanol via depots to filling stations, and subsequent combustion of bioethanol by end users in vehicles. As above, these calculations take into account the effects of possible surplus electricity from a CHP unit in the bioethanol plant, by means of avoided GHG emissions from displaced grid electricity, and the co-production of distillers' dark grains and solubles (DDGS) and beet pulp as animal feeds. This required the application of emissions factors for animal feed counterfactuals which are addressed elsewhere (see Section 5.11). It should again be noted that the emissions factors given in Table 5.24 are per odt of energy crop provided "at the farm gate" for consistency with the approach adopted by Alterra for energy crop production.

Table 5.24 Emissions factors for processing of energy crops for bioethanol production and use within EU27 region

Energy Crop	Value	Emissions Factor ($kgCO_2$-eq. odt^{-1} energy crop)		
		2010	**2020**	**2030**
Barley for Bioethanol Production and Use in EU27 Region	Low	42	66	81
	High	282	274	269
Maize for Bioethanol Production and Use in EU27 Region	Low	-28	-20	-15
	High	89	83	80
Sugar Beet for Bioethanol Production and Use in EU27 Region	Low	-35	-17	-10
	High	59	63	61
Wheat for Bioethanol Production and Use in EU27 Region	Low	-65	-42	-28
	High	159	155	153

The main factors that influence the range of emissions factors from the low to high values are the round trip distance for road transportation of energy crops to the bioethanol plant, the choice of energy source (natural gas-fired CHP or coal-fired boiler with grid electricity) in the bioethanol plant, the choice of animal feed counterfactual emissions factor, the round trip distance and mode of transportation of bioethanol from the plant to the depot, and the round trip road transport distance for bioethanol from the depot to the filling station. As apparent in Table 5.24, application of an avoided emissions factor for surplus electricity from the CHP unit in the bioethanol plant combined with a high emissions factor for the animal feed counterfactual can result in negative emissions factors for bioethanol production and use. As before, this can be counter-balanced by GHG emissions associated with energy crop production, as addressed separately by Alterra.

Table 5.25 summarises the emissions factors for transportation of miscanthus, reed canary grass and switchgrass bales from "the farm gate" to storage facilities, and miscanthus, reed canary grass and switchgrass chip transportation for drying, milling and pelletising, with transportation and combustion bales and pellets by end users for commercial/industrial heat generation, including ash transportation and disposal to landfill in the EU27 region for 2010, 2020 and 2030. These pathways are represented in the workbook, "EC BCI Crops Grass v04.xlsx", which determines GHG emissions in addition to those associated with cultivation and harvesting evaluated separately by Alterra. As before, results are presented in terms of odt of wood chip "at the farm gate". The main factors that influence the range of emissions factors from the low to high values were the choice of bales or pellets as the type of fuel produced, the round trip road transport distance for bales and chips, the use of natural or artificial drying, the round trip distance for transporting subsequent fuels to end users, and the round trip distance for road transportation of ash from fuel combustion.

Table 5.25 Emissions factors for processing of miscanthus, reed canary grass and switchgrass for fuel production and use within EU27 region

Energy Crop	Value	Emissions Factor (kgCO_2-eq. odt^{-1} energy crop)		
		2010	2020	2030
Miscanthus Fuel Production and Use in EU27 Region	Low	60	58	57
	High	252	242	231
Reed Canary Grass Fuel Production and Use in EU27 Region	Low	59	58	57
	High	229	216	205
Switchgrass Fuel Production and Use in EU27 Region	Low	58	57	55
	High	228	215	204

Table 5.26 summarises the emissions factors for provision of wood chips from poplar and willow in the EU27 region for 2010, 2020 and 2030. These pathways, which are represented in the workbook, "EC BCI Crops Wood v03.xlsx", consist of wood chip road transportation for drying and storage prior to distribution to end users. As noted previously, GHG emissions associated with cultivation and harvesting were evaluated separately by Alterra. Additionally, GHG emissions associated with fuel transportation and use are addressed separately in aggregated wood use (see Section 5.12). Emissions factors are provided in terms of odt of wood chip available "at the farm gate". The main factors that influence the range of emissions factors from the low to high values were the round trip road transport distance for wood chips, and the choice of drying with wood or fuel oil.

Table 5.26 Emissions factors for provision of wood chips from poplar and willow for fuel production and use within EU27 region

Energy Crop	Value	Emissions Factor (kgCO_2-eq. odt^{-1} energy crop)		
		2010	2020	2030
Wood Chip Fuel Production from Poplar and Willow in EU27 Region	Low	9.9	9.7	9.6
	High	24.1	23.1	19.7

Table 5.27 summarises the emissions factors for production of biogas from fodder maize in the EU27 region for 2010, 2020 and 2030. The workbook, "EC BCI Fodder Maize AD v02.xlsx", represents pathways which consist of road transportation of fodder maize from "the farm gate" and processing in small- and large-scale AD plants, taking into account subsequent digestate spreading. These GHG emissions calculations include avoided emissions due to the displacement of artificial fertilisers by digestate. GHG emissions associated with the cultivation and harvesting of fodder maize were evaluated separately by Alterra. Emissions factors are given in terms of MJ of fodder maize "at the farm gate". The main factor that influences the range of emissions factors from the low to high values is the choice of using a small-scale AD plant or large-scale, centralised AD plant, with subsequent impacts of modes of transport (tractors and trailers, or lorries, respectively) and round trip transport distances.

Table 5.27 Emissions factors for biogas production from fodder maize within EU27 region

Energy Crop	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} energy crop)		
		2010	2020	2030
Biogas Production from Fodder Maize in EU27 Region	Low	0.00340	0.00404	0.00348
	High	0.00406	0.00478	0.00422

5.10. GHG emissions associated with imports of biofuels from crops

GHG emissions associated with the production of biodiesel and bioethanol outside the EU27 region, and their transportation to and use in the EU27 region were determined using the pathway workbooks, "EC BCI Biodiesel Imports v06.xlsx", and "EC BCI Bioethanol Imports v09.xlsx". These pathway workbooks include the cultivation and harvesting of relevant crops, as well as subsequent conversion to biofuels, in the countries that represent appropriate regions specified in the VTT-TIAM model. GHG emissions associated with direct land use change in the countries could not be taken into account due to lack of necessary information.

Table 5.28 summarises the emissions factors for the production of biodiesel from soy beans in Argentina, representing the LAM region, and in the USA, and transportation to and use by combustion in end users' vehicles in the EU27 region for 2010, 2020 and 2030. The pathways in the workbook, "EC BCI Biodiesel Imports v06.xlsx", consist of soy bean cultivation and harvesting, drying, cooling and storage, road transportation to the biodiesel plant, conversion to biodiesel by extraction and esterification, transportation of biodiesel to the EU27 region and via depots to filling stations, and subsequent combustion of biodiesel by end users in vehicles. These calculations take into account the effects of possible surplus electricity from a CHP unit in the biodiesel plant, by means of avoided GHG emissions from displaced grid electricity, and the co-production of soy meal as animal feeds. This required the application of emissions factors for animal feed counterfactuals which are addressed elsewhere (see Section 5.11). Emissions factors are presented in terms of MJ of biodiesel delivered to end users. The main factors that influence the range of emissions factors from the low to high values were the choice of tillage or no tillage in soy meal cultivation in Argentina, and choice of soy bean cultivation without and with irrigation in the USA, the choice of energy source (natural gas-fired CHP or coal-fired boiler with imported grid electricity) in the biodiesel plant, the choice of animal feed counterfactual emissions factor, the modes of transportation and their round trip distances between the biodiesel plant and end users in the EU27 region.

Table 5.28 Emissions factors for production and use of imported biodiesel in EU27 region

Energy Crop*	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} biodiesel)		
		2010	2020	2030
Biodiesel Production from Soy Beans in LAM Region and Use in EU27 Region	Low	0.0793	0.0803	0.0800
	High	0.1005	0.1004	0.1001
Biodiesel Production from Soy Beans in USA and Use in EU27 Region	Low	0.0290	0.0283	0.0284
	High	0.0952	0.0933	0.0929

*See Table 1.1, Section 1.4, for definitions of regions

Table 5.29 summarises the emissions factors for the production of bioethanol from sugar cane in Brazil, representing the LAM region, from wheat in Russia, representing the CIS region, and from maize (corn) in the USA, and transportation to and use by combustion in end users' vehicles in the EU27 region for 2010, 2020 and 2030. The pathways in the workbook, "EC BCI Bioethanol Imports v09.xlsx" consist of sugar cane, wheat and maize cultivation and harvesting, drying, cooling and storage where necessary (wheat), road transportation to the bioethanol plant, conversion to biodiesel by fermentation, transportation of biodiesel to the EU27 region and via depots to filling stations, and subsequent combustion of bioethanol by end users in vehicles. As previously with imported biodiesel pathways, these calculations take into account the effects of possible surplus electricity from a CHP unit in the bioethanol plant, by means of avoided GHG emissions from displaced grid electricity, and the co-production of bagasse and DDGS as animal feeds. This required the application of emissions factors for animal feed counterfactuals which are addressed elsewhere (see Section 5.11). Emissions factors are presented in terms of MJ of bioethanol delivered to end users. The main factors that influence the range of emissions factors from the low to high values were the choice of manual or mechanical harvesting of sugar cane in Brazil, the choice of maize cultivation without or with irrigation in the USA, the choice of energy source (bagasse-fired CHP or boiler with imported grid electricity for sugar cane conversion, and natural gas-fired CHP or coal-fired boiler with imported grid electricity for wheat and maize conversion) in the biodiesel plant, the choice of animal feed counterfactual emissions factor, the modes of transportation and their round trip distances between the bioethanol plant and end users in the EU27 region.

Table 5.29 Emissions factors for production and use of imported bioethanol in EU27 region

Energy Crop*	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} biodiesel)		
		2010	2020	2030
Bioethanol Production from Sugar Cane in LAM Region and Use in EU27 Region	Low	0.0224	0.0226	0.0240
	High	0.0486	0.0467	0.0464
Bioethanol Production from Wheat in the CIS Region and use in EU27 Region	Low	0.0575	0.0495	0.0508
	High	0.1130	0.0977	0.0980
Bioethanol Production from Maize in USA and Use in EU27 Region	Low	0.0337	0.0273	0.0274
	High	0.0486	0.0386	0.0383

*See Table 1.1, Section 1.4, for definitions of regions

5.11. GHG emissions associated with animal feed counterfactuals

GHG emissions factors for counterfactuals to animal feeds co-produced with biofuels were required for the evaluation of indirect GHG emissions associated with the production and use of biodiesel and bioethanol outside and within the EU27. Specific counterfactuals were chosen on the basis that, as animal feeds, they were single products (not co-products) with similar crude protein basis and/or metabolizable energy basis to animal feeds co-produced in biodiesel and bioethanol plants from relevant crops. The GHG emissions associated with the production of these counterfactuals were evaluated using the workbook, "EC BCI Animal Feed Counterfactuals v05.xlsx". The list of animal feeds co-produced with biodiesel and bioethanol and their selected counterfactuals is provided in Table 5.30.

Table 5.31 summarises the emissions factors for the production of selected counterfactuals to animal feeds co-produced with biodiesel and bioethanol within and outside the EU27 region for 2010, 2020 and 2030. The emissions factors for counterfactuals are presented in terms of t of animal feed at given moisture content co-produced with a specific biofuel, taking into account different production assumptions and equivalence based on a crude protein basis or metabolizable energy basis. Low or high values for these emissions factors incorporate maximum or minimum values of national yields, respectively, for relevant crops in appropriate countries between 2004 and 2013. Additionally, low or high valued for emissions factors are based on processing, where relevant, with energy supplied by a natural gas-fired CHP unit or a coal-fired boiler and imported grid electricity, respectively. All other data used in the GHG emissions calculation are based on default values.

Table 5.30 List of animal feed co-products of biodiesel and bioethanol production and their selected counterfactuals

Biofuel Production*	Animal Feed Co-product	Counterfactual*
Biodiesel Production from Oilseed Rape in EU27 Region	Rape Meal	Faba Bean Meal Produced in EU27 Region
Biodiesel Production from Sunflowers in EU27 Region	Sunflower Meal	Faba Bean Meal Produced in EU27 Region
Biodiesel Production from Soy Beans in LAM Region	Soy Meal	Faba Bean Meal Produced in LAM Region
Biodiesel Production from Soy Beans in USA	Soy Meal	Faba Bean Meal Produced in USA
Bioethanol Production from Barley in EU27 Region	DDGS	Faba Bean Meal Produced in EU27 Region
Bioethanol Production from Maize in EU27 Region	DDGS	Faba Bean Meal Produced in EU27 Region
Bioethanol Production from Sugar Beet in EU27 Region	Beet Pulp	Potatoes Produced in EU27 Region
Bioethanol Production from Sugar Cane in LAM Region	Bagasse	Barley Straw Produced in LAM
Bioethanol Production from Wheat in CIS Region	DDGS	Faba Bean Meal Produced in CIS Region
Bioethanol Production from Maize in USA	DDGS	Faba Bean Meal Produced in USA

*See Table 1.1, Section 1.4, for definitions of regions

In particular, faba bean meal production includes cultivation and harvesting, road transportation, drying, storage and milling in the EU27 region, in Argentina representing the LAM region, in Russia representing the CIS region, and in the USA. Potato production includes cultivation, harvesting, road transportation and storage in the EU27 region. Barley straw production includes baling after barley harvesting, with extra fertiliser applications for straw removal and avoided incorporation, in Brazil representing the LAM region.

Table 5.31 Emissions factors for production of counterfactuals for animal feed co-produced with biofuels within and outside EU27 region

Animal Feed Counterfactual*	Value	Emissions Factor ($kgCO_2$-eq. t^{-1} of biofuel co-product)		
		2010	2020	2030
Faba Bean Meal Produced in EU27 Region Displaced by Rape Meal	Low	311	314	314
	High	595	597	592
Faba Bean Meal Produced in EU27 Region Displaced by Sunflower Meal	Low	259	262	261
	High	580	582	577
Faba Bean Meal Produced in LAM Region Displaced by Soy Bean Meal	Low	203	207	207
	High	414	419	418
Faba Bean Meal Produced in USA Displaced by Soy Bean Meal	Low	486	495	495
	High	922	932	931
Faba Bean Meal Produced in EU27 Displaced by Barley, Maize and Wheat DDGS	Low	136	138	137
	High	197	197	196
Potatoes Produced in EU27 Region Displaced by Beet Pulp	Low	41	37	37
	High	55	50	49
Barley Straw Produced in LAM Displaced by Bagasse	Low	-40	-39	-40
	High	-17	-17	-17
Faba Bean Meal Produced in CIS Region Displaced by Wheat DDGS	Low	205	206	204
	High	400	398	394
Faba Bean Meal Produced in USA Displaced by Maize DDGS	Low	198	201	201
	High	210	212	212

*See Table 1.1, Section 1.4, for definitions of regions

5.12. GHG emissions associated with aggregated wood use

Aggregated wood use is a specification from the VTT-TIAM model which covers the generation of energy from fuels derived from all sources of wood. GHG emissions associated with such aggregated wood use cover all activities following the production of wood fuel from all these sources. GHG emissions associated with the production of wood fuel have been addressed separately (see Sections 5.7, 5.8 and 5.9). Estimates of GHG emissions associated with aggregated wood use were derived using the pathway workbook, "EC BCI Aggregated Wood Use v03.xlsx". This workbook represents wood pellet road transport and combustion for residential heating and electricity generation, and wood chip road transportation and combustion for commercial/industrial-scale heating and CHP generation. All these pathways include road transportation of ash for disposal into landfill.

The CO_2 emissions from the combustion wood fuels derived from wood in forests are represented elsewhere (see Section 5.7), due to the evaluation of carbon sequestration in forests by the CARBINE model, and are not required for wood fuel derived from other sources, as carbon sequestration is not determined in the MITERRA-Europe model.

Hence, CO_2 combustion emissions are excluded from aggregated wood use. However, CH_4 and N_2O combustion emissions are necessarily included.

Table 5.32 summarises the emissions factors for aggregated wood fuel use in the EU27 region for 2010, 2020 and 2030. Emissions factors are presented in terms of MJ of wood fuel supply. The main factors that influence the range of emissions factors from low to high values are the choice of wood fuel as chips or pellets, the choice of mode of transport and round trip distance between the supply of wood fuel and the end use, the choice of end use as electricity generation or residential-scale heating, and the round trip distance for ash disposal.

Table 5.32 Emissions factors for aggregated wood fuel use in EU27 region

Aggregated Wood Use	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} wood fuel supply)		
		2010	2020	2030
Aggregated Wood Fuel Use in EU27 Region	Low	0.00277	0.00292	0.00293
	High	0.00730	0.00738	0.00720

5.13. GHG emissions associated with biofuel production from wood

Evaluation of the GHG emissions associated with the production of biofuels from wood and the subsequent use of these biofuels is undertaken in the pathway workbook, "EC BCI Wood Biofuels v04.xlsx". This workbook includes pathways for the production of bioethanol from wood by lignocellulosic processing in the EU27 region; the production of petrol and diesel blendstock (bio-oil) from wood by fast pyrolysis and hydrotreatment in the EU27 region; the production of biokerosene from wood by Fischer-Tropsch processing in the EU27 region, in Brazil representing the LAM region, and in Russia representing the CIS region; and the production of bioSNG from wood by gasification, its injection into gas grids, and subsequent transportation to end users in the EU27 region.

Table 5.33 summarises the emissions factors for producing biofuels and bioSNG from wood in the EU27 region and, where relevant, the LAM and CIS regions, and the subsequent supply and use these biofuels and bioSNG in the EU27 region for 2010, 2020 and 2030. Emissions factors are presented in terms of MJ of wood supply. The main factors that influence the range of emissions factors from low to high values are the choice of modes of transport and round trip distance for transporting wood chips to the biofuel plants; where relevant, the assumed overall thermal energy efficiency of Fischer-Tropsch processing; and the round trip distance for transporting ash for disposal to landfill. Negative emissions factors are possible for biokerosene production from wood due to the co-production of naphtha which results in avoided GHG emissions from the displaced production of naphtha from fossil fuel sources; and from surplus heat from bioSNG production which results in avoided GHG emissions from the displaced use of a natural gas-fired boiler.

Table 5.33 Emissions factors for production of biofuels and bioSNg from wood and their use in EU27 region

Biofuel/BioSNG*	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} wood supply)		
		2010	**2020**	**2030**
Bioethanol Production from Wood and Use in EU27 Region	Low	0.00808	0.00672	0.00673
	High	0.00917	0.00781	0.00782
Petrol and Diesel Blendstock Production from Wood and Use in EU27 Region	Low	0.00629	0.00628	0.00622
	High	0.00719	0.00717	0.00711
Biokerosene Production from Wood and Use in EU27 Region	Low	0.00014	-0.00039	-0.00036
	High	0.00128	0.00102	0.00103
Biokerosene Production from Wood in LAM Region and Use in EU27 Region	Low	0.0076	0.0063	0.0063
	High	0.0360	0.0347	0.0346
Biokerosene Production from Wood in CIS Region and Use in EU27 Region	Low	0.0042	0.0026	0.0025
	High	0.0324	0.0302	0.0298
BioSNG Production from Wood and Use in EU27 Region	Low	-0.00671	-0.00682	-0.00711
	High	0.00628	0.00673	0.00684

*See Table 1.1, Section 1.4, for definitions of regions

5.14. GHG emissions associated with black liquor use

The GHG emissions associated with the use of black liquor, as specified in the VTT-TIAM model, are assumed to be related to paper and card production other than that related to co-production with wood fuels from forests in the EU27 region. Additionally, it has been assumed that these emissions only refer to the combustion of black liquor, since activities involved in its recovery are already incorporated in the VTT-TIAM model. It should also be noted that GHG emissions due to black liquor recovery are expected to be comparatively small. Finally, these combustion emissions consist only of CH_4 and N_2O emissions, as the VTT-TIAM model does not represent the sequestration of carbon during the original growth of trees, thereby excluding the need to incorporate CO_2 emissions from the combustion of black liquor. Given assumed values for GWPs of 25 $kgCO_2$-eq. $kgCH_4^{-1}$ and 298 $kgCO_2$-eq. kgN_2O^{-1}, and the assumed net calorific value of black liquor of 11,800 MJ t^{-1} (weight as received), a constant emissions factor of 0.00224 $kgCO_2$-eq. MJ^{-1} was adopted here.

5.15. GHG emissions associated with solid biowaste use

Solid biowaste specified in the VTT-TIAM model is assumed to be composed of the organic fraction of municipal solid waste and other wastes generated in the EU27 region. The pathways for using solid biowaste for energy consist of incineration for CHP generation, and conversion to bioethanol by lignocellulosic processing. The pathway workbook, “EC BCI Biowaste Energy v05.xlsx”, represents these pathways. These include road transportation of solid biowaste and CHP generation by incineration with road transportation of ash for disposal to landfill, and bioethanol production by lignocellulosic processing followed by transportation of bioethanol via depots to filling station and subsequent use by combustion in end users' vehicles.

Evaluation of emissions factors has to take into consideration counterfactual disposal of solid biowaste. Consequently, the workbook, "EC BCI Biowaste Energy v05.xlsx", includes pathways for solid biowaste disposal to landfill without and with energy recovery, and incineration without energy recovery. These pathways are relevant to disposal options allowable for biodegradable wastes in the EU27 region between 2010 and 2050. In particular, it is expected that all waste disposal options could be available up to 2025 within the EU27 region. However, after 2025, it is intended that landfill disposal will no longer be an option for biodegradable wastes. Hence, the counterfactual emissions factors applied to the pathways for solid biowaste use accommodate these assumptions. It should also be noted that counterfactuals involving energy recovery introduce avoided GHG emissions from the assumed displacement of grid electricity.

Table 5.34 summarises the emissions factors for solid biowaste use and counterfactual disposal in the EU27 region for 2010, 2020 and 2030. Emissions factors are presented in terms of MJ of solid biowaste. The main factors that influence the range of emissions factors from low to high values were the choice of counterfactual solid biowaste disposal options (depending on timing pre- and post-2025); the round trip distance for road transportation of solid biowaste; in the case of incineration, the round trip distance for road transportation of ash for landfill disposal; and, in the case of lignocellulosic processing, the round trip distances involved in transporting bioethanol via depots to filling stations. The main factors that influence the ranges of emissions factors for counterfactual disposal from low to high values were the round trip distance for road transportation of solid biowaste and the available choice of disposal options (pre- and post-2025). It should be noted that, because of the application of emissions factors for certain counterfactual disposal options, the emissions factors for solid biowaste use can be negative.

Table 5.34 Emissions factors for solid biowaste use and counterfactual disposal in EU27 region

Biowaste Use/Counterfactuals	Value	Emissions Factor ($kgCO_2$-eq. MJ^{-1} solid biowaste)		
		2010	**2020**	**2030**
CHP Generation from Solid Biowaste Incineration in EU27 Region	Low	-0.0697	-0.0737	-0.0006
	High	0.000338	0.000391	0.000416
Bioethanol Production from Solid Biowaste and Use in EU27 Region	Low	-0.0863	-0.0900	-0.0170
	High	-0.0162	-0.0158	-0.0159
Counterfactual Solid Biowaste Disposal in EU27 Region	Low	0.000564	0.000529	0.000504
	High	0.0701	0.0741	0.00103

5.16. GHG emissions associated with solid waste disposal

In addition to solid biowaste disposal, GHG emissions are associated with the disposal of wood products and their counterfactuals at the end of their lives. Pathways are represented for the disposal of inert wastes (those which cannot decompose into GHG emissions) and wood products including paper and card. It has been assumed that inert wastes will be disposed to landfill at any time over the period under consideration. However, within the EU27 region the same constraints on solid biowaste or biodegradable wastes would apply to wood products (see Section 5.16). Hence, all disposal options, including wet landfill without energy recovery, would be available only up to 2025 in the EU27 region for wood products. After 2025, it is expected that landfill disposal options would not be allowed so that incineration is likely to be the main option for disposing wood products. Outside the EU27 region, it is possible that all disposal options might be available at any time for wood products.

All relevant inert product and wood product disposal pathways are represented in the workbook, "EC BCI Waste Disposal v03.xlsx". This includes inert disposal to landfill in all regions; disposal of wood products to wet landfill without and with energy recovery, and to incineration without and with energy recovery in the EU27 region; and disposal of wood products to wet landfill without energy recovery, and to incineration without and with energy recovery in Brazil representing the LAM region, in Russia representing the CIS region, in the USA and in Canada. Evaluation of GHG emissions associated with these inert and wood product disposal options include those from road transportation to disposal facilities, CO_2 and CH_4 emissions leakage from wet landfill sites without and with energy recovery, combustion emissions from landfill gas used in energy recovery, and from incineration, and GHG emissions associated with road transportation of ash from incineration plants to landfill disposal. It should be noted that CO_2 emissions from landfill leakage, landfill gas combustion and incineration are included because this derives from wood products associated with wood fuel production from forests. Hence, such CO_2 must be taken into account for consistency with original carbon sequestration by trees in the forests, as accommodated by the CARBINE model.

Table 5.35 summarises the emissions factors for inert waste and wood product disposal in the EU27, LAM and CIS regions, and in the USA and Canada for 2010, 2020 and 2030. Emissions factors are presented in terms of t of inert waste or wood product. The main factors that influence the range of emissions factors from low to high values are the round trip distance for road transportation of inert waste and wood products, choices of disposal options, and, in the case of incineration, the round trip distance for road transportation for ash to landfill disposal. It should be noted that the evaluation of GHG emissions associated with landfill with energy recovery (electricity generation) incorporates avoided emissions of displaced grid electricity in the regions under consideration. Likewise, the evaluation of GHG emissions associated with incineration with energy recovery (CHP generation) takes into account avoided emissions of displaced heating from natural gas-fired boilers and grid electricity for the regions in question.

Table 5.35 Emissions factors for inert waste and wood product disposal outside and within EU27 region

Inert Waste/Wood Product Disposal*	Value	Emissions Factor ($kgCO_2$-eq. per tonne inert waste or per tonne wood product)		
		2010	2020	2030
Inert Waste Disposal to Landfill in LAM Region	Low	6	6	6
	High	12	12	12
Wood Product Disposal in LAM Region	Low	776	807	833
	High	6928	6928	6928
Inert Waste Disposal to Landfill in CIS Region	Low	6	6	6
	High	12	12	12
Wood Product Disposal in CIS Region	Low	669	808	857
	High	6928	6928	6928
Inert Waste Disposal to Landfill in USA	Low	5	5	5
	High	11	11	11
Wood Product Disposal in USA	Low	809	854	881
	High	6921	6921	6921
Inert Waste Disposal to Landfill in Canada	Low	5	6	6
	High	11	12	12
Wood Product Disposal in Canada	Low	1042	842	994
	High	6927	6928	6928
Inert Waste Disposal to Landfill in EU27 Region	Low	5	5	5
	High	11	11	11
Wood Product Disposal in EU27 Region	Low	889	934	954
	High	2222	2278	1700

*See Table 1.1, Section 1.4, for definitions of regions

5.17. GHG emissions associated with biogas and waste gas use

The GHG emissions associated with biogas and waste gas use, as specified in the VTT-TIAM model, relate to the combustion of these gases for the generation of energy. Relevant pathways for this are represented in workbook, "EC BCI Biogas Use v02.xlsx". These pathways consist of biogas combustion for heating, small- and large-scale CHP generation, and small- and large-scale electricity generation. Additionally, a pathway is included for biogas upgrading and injection into the grid, transportation with potential CH_4 leakage, and combustion by end users. In all instances, CH_4 and N_2O emissions from combustion are taken into account but not CO_2 emissions, as the biogas has been derived from biogenic sources and carbon sequestration has not been accommodated in their growth during cultivation. In particular, the cultivation and harvesting of fodder maize has been addressed by Alterra using the MITERRA-Europe model and its conversion to biogas by means of anaerobic digestion is evaluated in another pathway workbook (see Section 5.9).

Table 5.36 summarises the emissions factors for biogas and waste gas use in the EU27 region for 2010, 2020 and 2030. Emissions factors are presented in terms of MJ of biogas supply. The main factor that influences the range of emissions factors from low to high values is the choice of biogas use pathway. For the low values of emissions factors, large-scale biogas-fired CHP generation was the chosen pathway. For the high values of emissions factors, the chosen pathway was biogas injection into the grid with combustion by end users.

Table 5.36 Emissions factors for biogas and waste gas use in EU27 region

Biogas/Waste Gas Use	Value	Emissions Factor (kgCO_2-eq. MJ^{-1} biogas supply)		
		2010	2020	2030
Biogas Use in EU27 Region	Low	0.00053	0.00057	0.00058
	High	0.00490	0.00467	0.00454

6. Discussion of final project results

6.1. Purpose

The purpose of this section is to:

- Describe how the various outputs produced in Tasks 2, 3 and 4 of this project have been integrated into final results.
- Present, assess and interpret the final results.

6.2. Development of final results workbook

Sections 3, 4 and 5 of this report have described the work done under Tasks 2 to 4 of this project to:

- Define and elaborate, quantitatively, scenarios for bioenergy consumption and supply in the EU up to 2050 (Task 2, Section 3)
- Estimate the impacts of increased bioenergy consumption in the EU on the management of crops and forests, on the supply of biomass for energy and non-energy uses, and on land-based carbon dynamics and biogenic carbon emissions, and CO_2 emissions associated with biogenic carbon of bioenergy (Task 3, Section 4)
- Estimate the (indirect) GHG emissions associated with the processes of bioenergy production, transport, processing, conversion and use of bioenergy in the EU, including associated impacts on consumption of biomass for non-energy uses (Task 4, Section 5).

The ultimate aim of this project has been to produce final quantitative results that consist of estimated total annual GHG emissions for the EU27 region under different agreed scenarios for the period between 2010 and 2050.The derivation of these estimated GHG emissions was achieved using the outputs produced in Tasks 2 to 4 from the VTT-TIAM model, the CARBINE model, the MITERRA-Europe/RothC model and pathway workbooks. Hence, it was necessary to bring all these outputs together in a consistent and interrelated manner to obtain estimates of total GHG emissions for the EU27 region under each scenario over the period from 2010 to 2050. This was achieved by developing and using an MS Excel workbook known as, “EC BCI Results v40.xlsx”.

The workbook contains worksheets for the low and high emissions cases of every scenario considered in this project, as well as worksheets based on the application of average emissions factors in the form of simple arithmetic means of the low and high values of emissions factors presented in Sections 5.3 to 5.17. Each worksheet is based on a standard structure which enabled outputs from the VTT-TIAM model, the CARBINE model, the MITERRA-Europe/RothC model and the pathway workbooks to be pasted into appropriate locations. As in the pathway workbooks, colour coding is used to identify those Cells into which values can be pasted (light blue) and those Cells which contain formulae which must not be overwritten (rose). Additionally, Cells that are colour coded light green contain linked data from worksheets which summarise emissions factors and equivalence between wood products and their counterfactuals, including derivation of average values from the low and high values presented in Sections 5.3 to 5.17. The scenario worksheets organise data into a fully documented matrix in which data for estimating GHG emissions are arranged in columns and entries for each year between 2010 and 2050 are set out in rows. Due to extensive data requirements to cover all necessary sources of GHG emissions and their supporting data, these workbooks are extremely wide; in total using columns A to TX (518 columns) for all basic calculations. At the end of the basic calculations, results are aggregated into a simpler table from which a suitable chart is derived. For convenience, these charts are provided in separate worksheets (distinguished by dark red tabs).

It should be noted that the different models and pathway workbooks generate outputs for different years within the period from 2010 to 2050. Although the CARBINE model produces outputs for every year, the VTT-TIAM model provides main outputs for the EU27 region every 5 years (2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050). However, for all imports into the EU27 region, the VTT-TIAM model gives outputs for 2010, 2020, 2030 and 2050. The MITERRA-Europe model generates emissions factors for energy crop cultivation and harvesting for every 5 years (2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050). For GHG emissions from direct land-use change and CO_2 emissions from soil organic carbon changes due to straw removal/avoided incorporation in the EU27 region, MITERRA-Europe/RothC generates emissions factors for every 10 years (2010, 2020, 2030, 2040 and 2050). Due to limitations in basic data, the emissions factors from the pathway workbooks are available for 2010, 2020 and 2030. In order to simulate estimated total GHG emissions for every year between 2010 and 2050 from these different outputs, formulae for simple linear interpolation were incorporated, as necessary, in the workbook for preparing final results. In the case of emissions factors from the pathway workbooks between 2030 and 2050, it was assumed that these remained constant with respect to their 2030 values. This assumption is likely to overstate GHG emissions between 2030 and 2050 due to expected but currently unknown improvements in production and manufacturing technologies during this period. However, it should be noted that, in general, the contributions from these emissions factors are small compared with more prominent sources of GHG emissions, especially CO_2 emissions from biogenic carbon associated with net carbon stock changes in forests.

There are a number of features in the final results workbook which enhances its functionality as well as its transparency. These include, prominently:

- Specification of the average life of co-produced harvested wood products and their counterfactuals (in years)
- Ratios between the mass of a given harvested wood product and the oven-dry mass of wood at the roadside in the forest
- The equivalence between a given harvested wood product and its counterfactuals (mass of counterfactual per unit oven-dry mass of wood required to produce the wood product).

It will be noted that the Cells for recording these parameters are colour-coded light blue in the workbook which means that values can be changed with the subsequent effect propagating through the calculations via suitable formulae in relevant Cells. Additionally, there are brief notes on the sources and basic features of the data, which are pasted into the workbook. In particular, information is recorded on the emissions factors chosen from pathway workbooks to generate low, average and high emissions versions of results for each scenario. When generating low and high emissions versions of results, in most cases, low and high values of emissions factors are selected, as would be expected for the low and high emissions versions of results for each scenario. However, when selecting either low or high values for emissions factors for harvested wood product counterfactuals and their end-of-life disposal, this logic is reversed. Hence, high values of emissions factors for the production and eventual disposal of these counterfactuals have been chosen for the low emissions cases of each scenario, and vice versa. This approach was adopted to ensure reasonable representation of the likely range of final results reflected in the low and high emissions cases of the scenarios. Finally, it should be noted that the estimated of total GHG emissions are given in terms of annual values expressed in millions of tonnes CO_2-equivalent ($MtCO_2$-eq. yr^{-1})[8], based on stated GWPs of 25 $kgCO_2$-eq. $kgCH_4^{-1}$ and 298 $kgCO_2$-eq. kgN_2O^{-1}.

6.3. Reprise of scenarios

The main project results are presented and discussed in detail in Section 6.5. An important part of this discussion is concerned with a comparison of results for the different scenarios for bioenergy supply and consumption developed in this project, including an assessment of the performance of the scenarios. Before proceeding, it is appropriate to reprise the descriptions of the scenarios as developed in Task 2. It is also important to clarify how the sensitivity of scenarios to assumed approaches to forest management and wood use, as part of the supply of forest bioenergy, has been investigated as part of the modelling in Task 3, and included in the results for scenarios.

The description of Task 2 in Section 3 of this report has described the development of six scenarios (Section 3.3):

- **A – 'Reference':** Following PRIMES 2013 reference scenario without additional targets for GHG emissions and renewable energy sources after 2020.
- **B – 'Carry on/unconstrained use'**: Decarbonisation scenario with a 40% GHG reduction target and 30% renewable energy sources target for 2030, but without sustainability criteria for solid and gaseous biomass (see Section 3.3.3). This scenario has the highest use of biomass for energy, coming from imports and domestic production and from forest and agricultural biomass sources.
- **C1 – 'Carry on/imported wood':** Decarbonisation scenario with a 40% GHG reduction target and 30% renewable energy sources target for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the

[8] Note that the workbook generally uses different notation conventions for units (generally closer to strict SI conventions). For example, units of $MtCO_2$-eq. yr^{-1} are given the notation Mt eq. CO_2/a.

additional biomass comes from imported forest-based biomass, hence the shorthand title for this scenario. However, it should be noted that the scenario also involves some increases in the importation of biofuels.

- **C2 – 'Carry on/domestic crops':** Decarbonisation scenario with a 40% GHG reduction target and 30% renewable energy sources target for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the biomass comes from domestic agriculture-based biomass.
- **C3 – 'Carry on/domestic wood':** Decarbonisation scenario with a 40% GHG reduction target and 30% renewable energy sources target for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Most of the biomass comes from domestic forest production.
- **D – 'Back off'**: Decarbonisation scenario with a 40% GHG reduction target and 30% renewable energy sources target for 2030, and with sustainability criteria for solid and gaseous biomass (see Section 3.3.3). Bioenergy consumption is lower, compared to the reference scenario, and replaced by other renewable energy sources.

It is important to understand the essential distinctions between these scenarios, as outlined below.

The Reference Scenario A represents the case where *existing policy targets* for renewable energy consumption and reductions in GHG emissions, set for 2020, should be met, but no further explicit policies or measures are taken to go further than the 2020 targets, either in terms of renewable energy consumption (including bioenergy consumption), or in terms of reductions in GHG emissions.

The various 'Carry on' Scenarios (B, C1, C2 and C3) represent cases in which policies and measures with regard to renewable energy consumption and reductions in GHG emissions do go further than the existing 2020 targets, by setting more ambitious targets for 2030. The individual 'Carry on' Scenarios represent different options for levels of consumption of bioenergy beyond the 2020 targets, and particular sources of bioenergy supply:

- B – highest use of biomass for energy, from all sources
- C1 – emphasises the consumption of imported forest bioenergy
- C2 – emphasises the consumption of bioenergy from energy crops and agricultural biomass grown in the EU region
- C3 – emphasises the consumption of forest bioenergy, supplied from forests in the EU region.

Scenario D ('Back off') also represents a situation in which policies and measures go further than the existing 2020 targets, by setting more ambitious targets for 2030. However, the consumption of bioenergy as a renewable energy source for meeting these targets is de-prioritised post 2020. Consequently, targets post-2020 have to be met by consuming other sources of energy and/or achieving greater energy efficiency.

6.3.1. Approaches to forest management and wood use

For each Task 2 scenario, the forest modelling exercise explored how forest bioenergy supply, co-production of material products, and consequent impacts on forest carbon stocks and GHG emissions, might depend on approaches taken to forest management and wood use. This was necessary because, as established in Task 1, specific approaches to forest management and the utilisation of wood can have a strong influence on the GHG emissions associated with forest bioenergy (Matthews *et al.*, 2014a).

Section 4.8.3 describes how two contrasting approaches were defined, referred to as the 'Precautionary' approach and the 'Synergistic' approach.

The 'Precautionary' approach was designed to represent a plausible set of changes in forest management and wood use to supply increased quantities of forest bioenergy in the EU. Specifically, the definition of the 'Precautionary' approach allowed for the existence of some sustainability criteria, e.g. aimed at protecting against the degradation of forest areas and ensuring their long-term productive potential. However, the 'Precautionary' approach is also based on the assumption of an absence of additional supporting policies and measures, or market-driven positive actions, which may aim to conserve or enhance forest carbon stocks alongside harvesting for bioenergy.

In broad terms, with reference to the decision tree in Figure 2.1a to 2.1d (see Section 2.4), the 'Precautionary' approach involved assumptions that implied some discouragement or de-prioritisation of higher risk options for the production of forest bioenergy. In the context of the decision tree in Figures 2.1a to 2.1d, Section 2.4, this implies that a number of the negative-risk and low-risk options are not actively pursued.

The 'Synergistic' approach included the principles of the 'Precautionary' approach, but also involved assumptions implying the encouragement or prioritisation of lower risks options for the production of forest bioenergy. The 'Synergistic' approach was designed to represent a situation in which additional policies or measures may be taken that actively support the production of forest bioenergy with negative, relatively low or moderate risks of significant associated GHG emissions, as indicated by the decision tree in Figures 2.1a to 2.1d, Section 2.4. Some of these actions may also be market-driven to some extent.

The 'Synergistic' approach also involved different assumptions about the supply of forest bioenergy to the EU from external regions. Specifically, for the LAM region, and with particular regard to the country of Brazil, an assumption was made that the increased demand for bioenergy in the EU27 region would lead to a market response, involving the establishment of high-productivity plantations dedicated to bioenergy production on formerly abandoned and degraded agricultural land.

In defining the detailed assumptions for both the 'Precautionary' and 'Synergistic' approaches, a key assumption was made that sustainability criteria would preclude certain activities with significant negative impacts on forest carbon stocks and forest growing stock in general. The reference to sustainability criteria in the development of the scenarios in this project has been discussed in Sections 3.3.3 and 3.5, and also Appendices 3 and 4. It should also be noted that wider sustainability criteria are already commonly applied in forestry with regard to wood production, e.g. strongly discouraging wood production that leads to deforestation. Accordingly, in the development of the scenarios, precluded activities included permanent deforestation and the replacement of areas of high forest with plantation forests grown on very short rotations. However, whilst some high-risk options for forest bioenergy supply were excluded, others were still included in the scenarios, in particular, the possibility of introducing management for production in forest areas where this was not previously practiced. Such introduced management also involved the co-production of bioenergy in conjunction with material wood products, which have the potential to displace counterfactual products. However, as discussed below, the assumptions involved in calculating the main project results with regard to the utilisation of material wood products were not optimised to achieve reductions in GHG emissions.

For each of the scenarios, the CARBINE model was applied to make projections of:

- Levels of forest biomass supply (for use as bioenergy)
- Marginal impacts (positive and/or negative) on supplies of material wood products
- Impacts on forest carbon sequestration and emissions
- Indirect GHG emissions associated with forest management operations.

The modelling approach and assumptions have been described in detail in Section 4 of this report. Two sets of outputs were produced for each scenario, referring to the assumptions under the ‘Precautionary’ approach and ‘Synergistic’ approach respectively. These outputs were integrated into the final results workbook, to enable the calculation of final results for each scenario in combination with outputs for either the ‘Precautionary’ or ‘Synergistic’ approach to forest management and wood use. The inclusion of these outputs, in combination with the low, average or high emissions factors from the pathway workbooks, permitted the exploration of uncertainties in results, and also the potential sensitivity of outcomes to the approaches taken in the forestry sector to meeting targets for forest bioenergy supply, as specified for each scenario. These uncertainties and sensitivities are discussed further in Sections 6.7 and 6.8 respectively, following consideration of the main project results in Section 6.5.

The main project results for the annual GHG emissions associated with the scenarios have been calculated using average emissions factors and refer to the ‘Precautionary’ approach to forest management and wood use. The selection of the ‘Precautionary’ approach for representation in the main project results followed from its conception, which has been described above.

Results calculated using average emissions factors and referring to the ‘Synergistic’ approach to forest management are considered as part of the assessment of uncertainties and sensitivities in results. Specifically, these results give an indication of the extent to which active support for positive approaches to forest management and wood use could influence the outcomes of the scenarios in terms of GHG emissions.

The application of average emissions factors in calculating the results as described above, particularly for the estimation of impacts on GHG impacts due to material wood co-products displacing counterfactual products, is an appropriate approach, since it is impossible to be more specific about 'most likely' values within the ranges defined. However, it follows that the main final project results, based on such average emissions factors, reflect a scenario in which no specific efforts are made to favour options for the use of material wood products that involve low GHG emissions for their manufacture and disposal, or to displace GHG emissions-intensive counterfactual products, i.e. the utilisation of material wood products is not optimised to achieve reductions in GHG emissions. It should be noted that, in principle, measures could be taken to encourage the recycling of wood products, and to ensure that their eventual disposal involves approaches that minimise GHG emissions. Additionally, measures could be taken to promote the use of material wood products to displace counterfactuals with high associated GHG emissions. However, this may be challenging to achieve in practice.

As explained in Section 4.8.4, the approach to representing changes to forest management to increase the supply of forest bioenergy to the EU region involved regional variations, particularly with regard to the relative emphasis on:

- Increasing the extraction of wood in a proportion of the area of forest already under management for wood production ('increased extraction')
- Re-assigning a proportion of the area of forest not currently under management for wood production, to introduce management for production ('introduced production').

These variations have implications for the resultant estimates of GHG emissions associated with forest bioenergy supplied from different geographical regions, as discussed further in Section 6.7.

6.4. GHG emissions contributing to final results

As explained in Section 6.2, the various project outputs have been integrated to form the final quantitative results of this project, which consist of estimated total annual GHG emissions for the EU27 region under different agreed scenarios for the period between 2010 and 2050. It is important to understand that a number of different sources of GHG emissions are taken into account in developing these estimates:

- GHG emissions from the combustion of fossil fuels within the EU27 region, prominent GHG emissions associated with the supply of fossil fuels within the EU27 region, and prominent GHG emissions from agricultural activities related to food production in the EU27 region; these sources are referred to, collectively and in shortened form, as "EU Emissions (non-biomass)"

- Indirect GHG emissions associated with the supply of imported fossil and nuclear fuels, and electricity into the EU27 region; these sources are referred to as "Imported Fossil and Nuclear Fuels, and Electricity"

- Direct and indirect GHG emissions, including CO_2 emissions associated with biogenic carbon and due to net forest carbon stock changes, associated with the supply of wood fuels from outside and within the EU27 region and co-produced harvested wood products (HWP), their counterfactuals and their end-of-life disposal; these sources are referred to as "LAM Wood Fuel to EU/HWP Co-products"[9] , "CIS Wood Fuel to EU/HWP Co-products", "USA Wood Fuel to EU/HWP Co-products", "CAN Wood Fuel to EU/HWP Co-products", and "EU Wood Fuel/HWP Co-products"

- Indirect GHG emissions associated with EU27-region agricultural biomass, consisting of the production of wood fuel from arboricultural arisings, and the production and use of straw fuel as well as net CO_2 emissions from soil organic carbon changes due to straw removal/avoided straw incorporation; these sources are referred to as "EU Agricultural Biomass"

- Indirect GHG emissions associated with EU27-region energy crops, including all energy crop cultivation and harvesting as well as GHG emissions from direct land-use change; biodiesel production from oilseed rape and sunflowers, and bioethanol production from barley, maize, sugar beet and wheat, accounting for animal feed co-product counterfactuals, and use; wood fuel production from poplar and willow; fuel production and use from miscanthus, reed canary grass and switchgrass; and fodder maize processing by anaerobic digestion; these sources are referred to as "EU Energy Crops"

- Indirect GHG emissions associated with EU27-region aggregated wood fuel use, including transportation within the EU27 region, combustion for heating, CHP and electricity generation: lignocellulosic processing for bioethanol production and use; fast pyrolysis and hydrotreatment for petrol and diesel blendstock production and use; gasification for bioSNG production and use; and Fischer-Tropsch processing for biokerosene production and use; these sources are referred to as "EU Aggregated Wood Use"

- Indirect GHG emissions associated with biodiesel imports to the EU27 region, consisting of soy bean cultivation and harvesting, and biodiesel production, accounting for animal feed co-product counterfactuals, transportation and use; these sources are referred to as "Imported Biodiesel"

- Indirect GHG emissions associated with bioethanol imports to the EU27 region, consisting of maize, sugar cane and wheat cultivation and harvesting, and bioethanol production, accounting for animal feed co-product counterfactuals, and use; these sources are referred to as "Imported Bioethanol"

- Indirect GHG emission associated with biokerosene imports to the EU27 region, consisting of petrol blendstock and biokerosene production from wood; these sources are referred to as "Imported Biokerosene"

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[9] It should be noted that, in fact, no co-production of material wood products (HWP) is associated with forest bioenergy supply from the LAM region (i.e. Brazil), see Section 4.8.3.

- Indirect GHG emissions associated with EU27 region black liquor use, consisting of combustion in mainstream paper and card production[10]; these sources are referred to as "EU Black Liquor"
- Indirect GHG emissions associated with EU27 solid biowaste use, consisting of transportation, incineration for CHP generation, and bioethanol conversion and use, accounting for counterfactual solid biowaste disposal; these sources are referred to as "EU Solid Biowaste"
- Indirect GHG emissions associated with EU27 region biogas and waste gas use, including biogas-fired heat, CHP and electricity generation, and biogas grid injection and use by combustion; these sources are referred to as "EU Biogas and Waste Gas".

The preceding list of GHG emissions sources demonstrates how this project has been designed to assess, comprehensively, impacts in terms of GHG emissions arising from increased consumption of biomass for energy in the EU. This is the approach required when undertaking an assessment of the impacts of a strategic policy or business decision, as determined by the conventions of consequential LCA (see Section 4 of the Task 1 report for this project, Matthews *et al*., 2014a). According to the conventions of LCA, the system boundary adopted for estimating emissions needs to encompass all of the parts of the system (and associated activities and processes) relevant to addressing the research question that has been stated. Owing to the nature of research questions associated with consequential LCA studies (such as in the case of this project), systems boundaries in consequential LCA frequently enclose a very large part of the world.

The system boundary adopted in this project flows from the research question or goal of the LCA study, which has been stated in the project purpose in Section 1.2.2 of this report. The LCA goal is stated as:

"to quantify the global emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources resulting from implementation of possible EU policies represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050".

The discussion of the project purpose in Section 1.2.2 notes that the consideration of possible policies for future energy consumption within the EU forms the starting point for the LCA. However, to assess the stated goal, it is necessary to account for subsequent prominent GHG emissions both within the EU and outside the EU due to the provision of imports of energy, including bioenergy, over a given period of time. Additionally, it is necessary to capture the changes in GHG emissions due to bioenergy displacing non-biomass energy and, where appropriate, non-energy products, referred to generally as 'counterfactuals'. This approach leads naturally to the requirement to consider the range of sources of GHG emissions identified in the preceding list. An important point to note about such a comprehensive assessment is that it covers GHG emissions that are

[10] This is separate from marginal paper and card production associated with wood fuel supply from forests in the EU27 region which is included elsewhere ("EU Wood Fuel/HWP Co-Products").

external to, as well as included in, national GHG inventories reported by EU Member States, or currently accounted for by EU Member States under the Kyoto Protocol. It follows that the assessment undertaken in this project is very thorough, going broader than considering just the impacts of potential bioenergy consumption on GHG emissions that would need to be reported in emissions inventories or would need to be accounted for by EU Member States.

Figure 6.1 shows an example of the final project results, specifically the estimated total annual GHG emissions over the period 2010 to 2050 for the Reference Scenario A, calculated using average emissions factors, and referring to the 'Precautionary' approach to forest management and wood use. This illustrates the relative magnitudes of the contributions to overall results made by the various categories of emissions sources listed above.

It is evident from Figure 6.1 that the biggest single contribution to total annual GHG emissions (and to changes over the period 2010 to 2050) is due to the category "EU emissions (non-biomass)". The contributions due to other sources of emissions are generally small. However, there are notable secondary contributions due to "Wood Fuel/HWP Co-Products" of various origins and due to "Imported Fossil Fuel and Nuclear Fuels, and Electricity". A complete set of graphs, such as illustrated in Figure 6.1, for all scenarios and illustrating sensitivity to assumptions, is given in Appendix 12 of this report. It is apparent from these graphs that the pattern of contributions to annual GHG emissions due to different sources as displayed in Figure 6.1 is also observed more generally in the results for all scenarios, although with some notable variations as discussed in Sections 6.6 and 6.7.

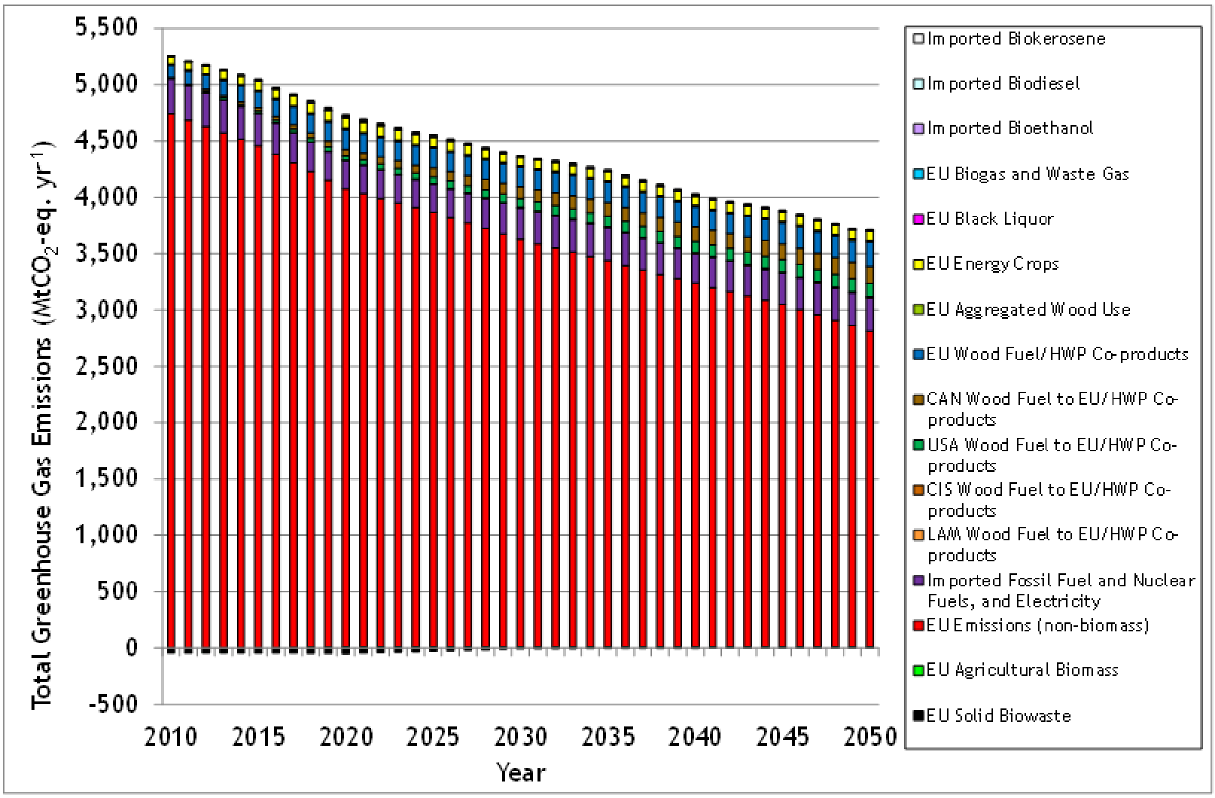

Figure 6.1. An example of final project results, showing contributions from various sources to total GHG emissions over time. Based on Reference Scenario A, calculated using average emissions factors and refer to the Precautionary' approach to forest management and wood use.

6.4.1. Understanding the impacts of bioenergy on contributions to total GHG emissions

It is important to understand how the impacts of bioenergy consumption are represented in graphs of results such as in Figure 6.1 and Appendix 12, because the impacts appear in several of the contributions to total annual GHG emissions. Specifically:

- Various changes in GHG emissions associated with different levels of bioenergy use are represented in a number of the different contributions to total annual GHG emissions. Relevant types of contributions to emissions in various categories include biogenic carbon emissions (and/or sequestration), indirect emissions associated with biomass production, processing and conversion, and GHG emissions associated with non-energy products of biomass (e.g. animal feed, material wood products) and the displacement of counterfactuals.
- The reductions in GHG emissions, specifically due to bioenergy displacing other energy sources are only represented, implicitly, in one contribution, i.e. "EU emissions (non-biomass)".

The full impacts of bioenergy use on total annual GHG emissions therefore need to be understood as a net outcome across a number of the contributions to emissions, such as illustrated in Figure 6.1. This holistic approach to the assessment of GHG emissions due to consumption of bioenergy is consistent with the approach of consequential LCA, which is concerned with the assessment of the global consequences (in this case in terms of GHG emissions) of taking the set of actions assumed in defining the scenarios for bioenergy consumption, as developed in this project. However, the approach requires that the results are interpreted very carefully. In particular, as discussed in detail in Sections 6.9.1 to 6.9.3, the projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. As a consequence, the contribution made specifically by bioenergy to net changes in GHG emissions over time is difficult to discern from overall results for total annual GHG emissions such as shown in Figure 6.1. An assessment of the specific contributions due to bioenergy requires further, detailed analysis, which is the subject of discussions in Sections 6.6, 6.7 and 6.9.

6.5. Assessment of main project results

Figure 6.2 shows the main results for all six scenarios developed in this project. The figure shows trajectories of total annual GHG emissions over time, plotted for each scenario. As explained in Section 6.3, these trajectories have been calculated using average emissions factors and refer to the 'Precautionary' approach to forest management and wood use.

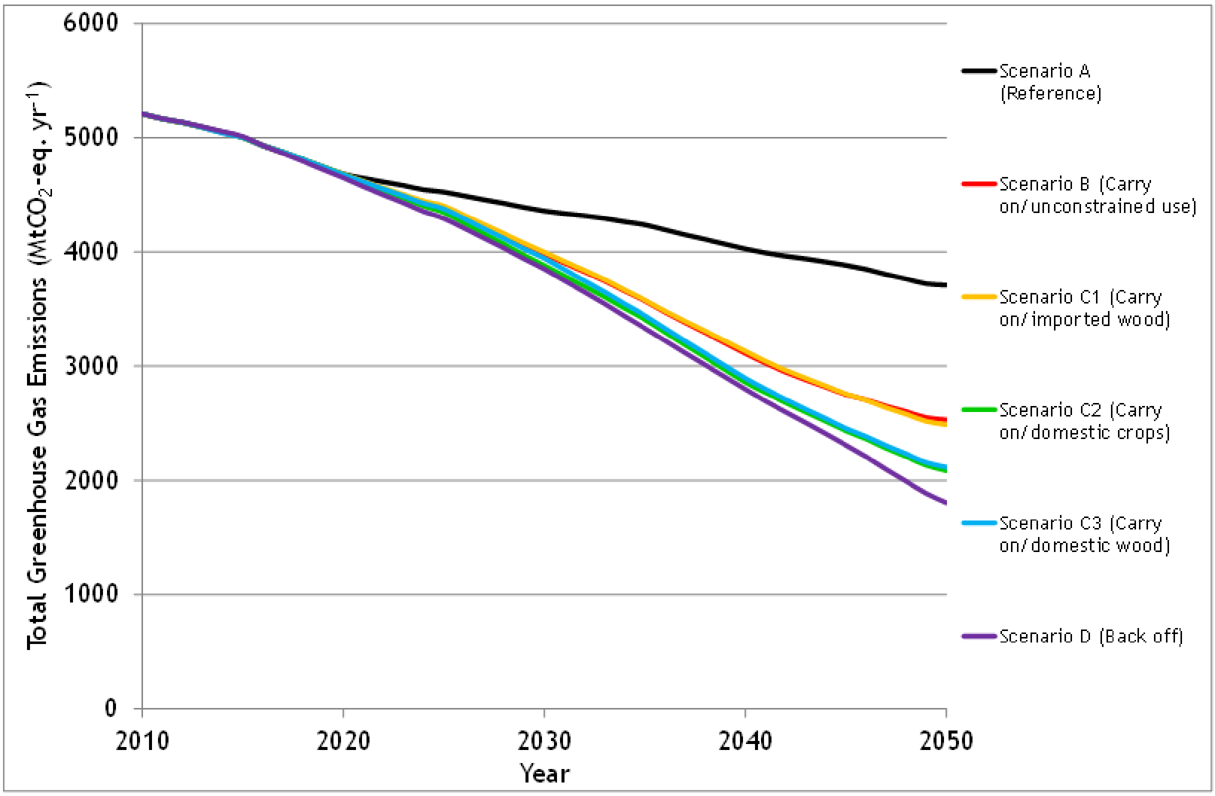

Figure 6.2. Trajectories of total GHG emissions over time for all scenarios, based on average emissions factors and referring to the 'Precautionary' approach to forest management and wood use.

6.5.1. General trends in GHG emissions

Two critical observations can be made immediately about the general trend in trajectories of total annual GHG emissions for all scenarios:

1. The trends for all trajectories are consistently and significantly downwards, i.e. total annual GHG emissions are reduced over time.
2. The reductions in total annual GHG emissions over time associated with trajectories for all the 'Carry on' Scenarios are much more pronounced than for the Reference Scenario A.

These observations lead to a crucial conclusion: *If bioenergy contributes towards future (renewable) energy supply in the EU region, it is also possible to achieve overall reductions in total annual GHG emissions.*

This conclusion is important, since it suggests that some published reports and opinions on bioenergy may have exaggerated the risks due to biogenic carbon emissions, if bioenergy, particularly forest bioenergy, were to be involved significantly in future energy supply (examples include Walker *et al*., 2010; EEA, 2011; Haberl *et al*., 2012; Holtsmark, 2012ab, 2013, 2015; RSPB, 2012; Schulze *et al*., 2012; Searchinger, 2012).

However, as already noted in Section 6.4.1, the projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. As a consequence, the contribution made specifically by bioenergy to net changes in GHG emissions over time is difficult to discern from overall results for total annual GHG emissions. An assessment of the specific contributions due to bioenergy requires further, detailed analysis, which is the subject of discussions in Sections 6.6, 6.7 and 6.9.

A further, equally important conclusion may be drawn from the observation that the trend in the trajectory of total annual GHG emissions for Scenario D ('Back off') is also consistently and significantly downwards: *This has some implications:*

- *All of the scenarios considered in this project representing different possible EU policies with regard to bioenergy, i.e. involving continued or increased bioenergy consumption in some form, or a backing off from consumption of bioenergy, can achieve reductions in GHG emissions*
- *Scenarios involving further actions towards decarbonisation, involving either increased consumption of bioenergy, or the de-prioritisation of bioenergy post 2020, can achieve significant improvements in reductions in GHG emissions, compared with simple continuance of 2020 policies, i.e. taking no further action beyond existing 2020 targets*
- *It follows that, in the context of future development of EU energy policy, the 'bioenergy option' may be viewed as neither a 'show-stopper' nor a 'must-have' from*

the simple perspective of achieving overall reductions in total annual GHG emissions alone.

6.5.2. Comparison of total GHG emissions for scenarios

An essential assessment of the final project results involves comparing the estimated reductions in total GHG emissions achieved by the various scenarios by specified years. An initial graphical comparison is possible by considering the results for projected total annual GHG emissions shown in Figure 6.2.

As already highlighted in Section 6.5.1, all scenarios lead to overall reductions in total annual GHG emissions, none involve overall increases in GHG emissions. Differences in the estimated total annual GHG emissions for the various scenarios do not become significant until after 2020. This is because all the scenarios are based on very similar assumptions about climate and energy policies and levels of biomass consumption for energy up to 2020, i.e. as implied by existing EU bioenergy policies. Beyond 2020, the estimates of total annual GHG emissions generally vary according to the scenario. All scenarios involving further development of EU policies with regard to bioenergy (either 'Carry on', or 'Back off') achieve significantly bigger reductions in GHG emissions post-2020, when compared with Reference Scenario A, which represents the continuation of existing EU policies. Additionally, differences can be observed between all scenarios in terms of total annual GHG emissions reductions achieved by 2050, although the distinctions between the 'Carry on' and 'Back off' Scenarios are relatively small, compared with differences between these scenarios and Reference Scenario A.

A numerical comparison of scenarios in terms of GHG emissions reductions is presented in Table 6.1, which shows the reduction in total annual GHG emissions achieved by the various scenarios in years 2020, 2030 and 2050, compared with a base year of 2010. It must be stressed that the results in Table 6.1 should not be interpreted as an assessment of whether internationally agreed targets for GHG emissions reductions within the EU region (subject to specific reporting conventions or accounting rules) may or may not be met. First of all, the base years referred to in policies setting targets for reductions in GHG emissions are different to 2010 (e.g. the base year in the Kyoto Protocol is 1990). Furthermore, as highlighted in Section 6.4, the results developed in this project have been calculated on a different basis to the GHG emissions that would be reported by EU Member States as part of national GHG emissions inventories, or accounted for as part of international commitments to reduce GHG emissions. The estimates of total GHG emissions derived in this project effectively represent global GHG emissions which would be influenced by EU policies with regard to energy consumption, particularly bioenergy consumption. This means that the system boundary encompassing the estimated emissions is very wide (see Section 6.4). This is an appropriate approach, given the previously-stated project purpose, and also enables the assessment of the global consequences of relevant EU policies.

Table 6.1 Reductions in total annual GHG emissions estimated for scenarios compared with 2010 levels

Scenario	Reduction in total annual GHG emissions for year, relative to 2010 ($MtCO_2$-eq. yr^{-1} and %)					
	2020		2030		2050	
	$MtCO_2$	%	$MtCO_2$	%	$MtCO_2$	%
A (Reference)	528	10.1	850	16.3	1 499	28.8
B (‘Carry on/ unconstrained use’)	537	10.3	1 228	23.6	2 678	51.4
C1 (‘Carry on/imported wood’)	530	10.2	1 211	23.2	2 721	52.2
C2 (‘Carry on/domestic crops’)	534	10.2	1 328	25.2	3 123	60.0
C3 (‘Carry on/domestic wood’)	535	10.3	1 265	24.3	3 093	59.4
D (‘Back off’)	560	10.8	1 359	26.1	3 404	65.4

Notes to Table 6.1:

1 These results represent contributions to global GHG emissions potentially arising from EU energy policy, i.e. GHG emissions due to EU policies occurring both within and externally to the EU region. Hence, these results should not be confused with an assessment of whether internationally agreed targets for emissions reductions within the EU region (subject to specific reporting conventions or accounting rules) may or may not be met.

2 Total GHG emissions estimated for the base year are 5208 $MtCO_2$-eq. yr^{-1}.

3 Based on results calculated by applying average emissions factors and ‘Precautionary’ assumptions about forest management and wood use involved in the supply of forest bioenergy.

By 2020, all scenarios lead to a reduction in total annual GHG emissions of typically 530 $MtCO_2$-eq. yr^{-1} (or 10%). By 2030, all scenarios involving further development of existing EU policies on energy (especially bioenergy) have diverged from the Reference Scenario A, typically attaining reductions in total annual GHG emissions of between 1,200 and 1,360 $MtCO_2$-eq. yr^{-1} (23% to 26%). The emissions reduction associated with the Reference Scenario A in 2030 is 850 $MtCO_2$-eq. yr^{-1} (16%). By 2050, these scenarios lead to varying levels of reductions in total annual GHG emissions:

- The largest reduction in total annual GHG emissions is associated with Scenario D (‘Back off’) at about 3.4 $GtCO_2$-eq. yr^{-1}, or 65% compared with 2010 levels
- Scenarios C2 (‘Carry on/domestic crops’) and C3 (‘Carry on/domestic wood’) lead to similar total annual GHG emissions reductions of about 3.1 $GtCO_2$-eq. yr^{-1}, or 60% compared with 2010 levels
- Scenarios B (‘Carry on/unconstrained use’) and C1 (‘Carry on/imported wood’) lead to similar total annual GHG emissions reductions of about 2.7 $GtCO_2$-eq. yr^{-1}, or 52%, compared with 2010 levels
- The Reference Scenario A leads to the smallest reduction in total annual GHG emissions by 2050, at about 1.5 $GtCO_2$-eq. yr^{-1}, or 29% compared with 2010 levels.

The greatest reductions in total annual GHG emissions are achieved under the ‘Back off’ Scenario D. However, the reductions achieved by the various ‘Carry on’ Scenarios are also significant, and quite close to Scenario D, in the case of Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood'). The reduction in total annual GHG emissions achieved by 2050 in Scenarios C2 and C3 (about 3.1 $GtCO_2$-eq. yr^{-1}) is within 10% of the reduction for Scenario D (3.4 $GtCO_2$-eq. yr^{-1}). However, if the absolute level of total annual GHG emissions in 2050 is considered, the results for Scenarios C2 and C3 (about 2.1 $GtCO_2$-eq. yr^{-1}) are about 16% greater than for Scenario D (1.8 $GtCO_2$-eq. yr^{-1}).

In conclusion, the above assessment of the final project results, based on comparison of the estimated reductions in total GHG emissions achieved by the various scenarios, reinforces the conclusions based on the assessment of general trends in Section 6.5.1, i.e. the various decarbonisation scenarios all achieve bigger reductions in total annual GHG emissions, compared with the Reference Scenario A (a reduction of at least 2.7 $GtCO_2$-eq. yr^{-1}, as opposed to 1.5 $GtCO_2$-eq. yr^{-1} under Reference Scenario A, between 2010 and 2050).

Furthermore, the results suggest a ranking in the outcomes achieved by the decarbonisation scenarios, in terms of reductions in total annual GHG emissions, relative to the Reference Scenario A:

- *A decarbonisation scenario involving de-prioritisation of bioenergy consumption in the EU post 2020 (Scenario D, 'Back off') achieves the biggest improvement in total annual GHG emissions reductions*
- *Decarbonisation scenarios emphasising the increased supply of bioenergy from domestic agricultural or forest bioenergy sources post 2020 (Scenario C2, 'Carry on/domestic crops' and Scenario C3, 'Carry on/domestic wood') achieve marginally smaller improvements in total annual GHG emissions reductions, compared with the 'Back off' Scenario D, although the outcomes for Scenarios C2, C3 and D in terms of the GHG emissions reductions achieved by 2050 are quite close (respectively 3.1, 3.1 and 3.4* $GtCO_2$*-eq.* yr^{-1} *between 2010 and 2050).*
- *Decarbonisation scenarios emphasising the increased supply of forest bioenergy imported from outside the EU post 2020 (Scenario B, 'Carry on/unconstrained use' and Scenario C1, Carry on/imported wood') achieve the smallest improvements in total annual GHG emissions reductions. However, the outcomes for Scenarios B, C1, C2 and C3, in terms of GHG emissions reductions achieved by 2050, are quite close (respectively 2.7, 2.7, 3.1 and 3.1* $GtCO_2$*-eq.* yr^{-1} *between 2010 and 2050).*

It is important to understand the underlying causes of the ranking exhibited amongst the decarbonisation scenarios, in terms of reductions in GHG emissions achieved, particularly in the case of differences between Scenarios C2 and C3 on the one hand (which emphasise the supply of bioenergy from domestic sources), and Scenarios B and C1 on the other hand, which involve significant contributions to (forest) bioenergy supply from regions outside the EU. This is discussed further in Sections 6.6, 6.7.1 and 6.9. It is also important to understand the causes of differences between the various 'Carry on' Scenarios and the 'Back off' Scenario D. This is discussed further in Sections 6.6 and 6.9.

6.6. Sources of changes in total annual GHG emissions

The reductions in total annual GHG emissions calculated for all scenarios developed in this project are the overall outcome of a number of changes in contributions to GHG emissions across a number of categories. This point has already been discussed in detail in Section 6.4. The detailed changes in contributions to total annual GHG emissions vary with scenario. To illustrate this point, Figures 6.3a and 6.3b show the magnitudes of the contributions to overall results in the years 2030 and 2050 for each scenario, as made by the various categories of emissions sources listed in Section 6.4. These results have been calculated using average emissions factors and refer to the 'Precautionary' approach to forest management and wood use. The variable contributions from different categories are very apparent in both figures, but most apparent in the results for the year 2050 (Figure 6.3b), for reasons discussed in Section 6.6.1.

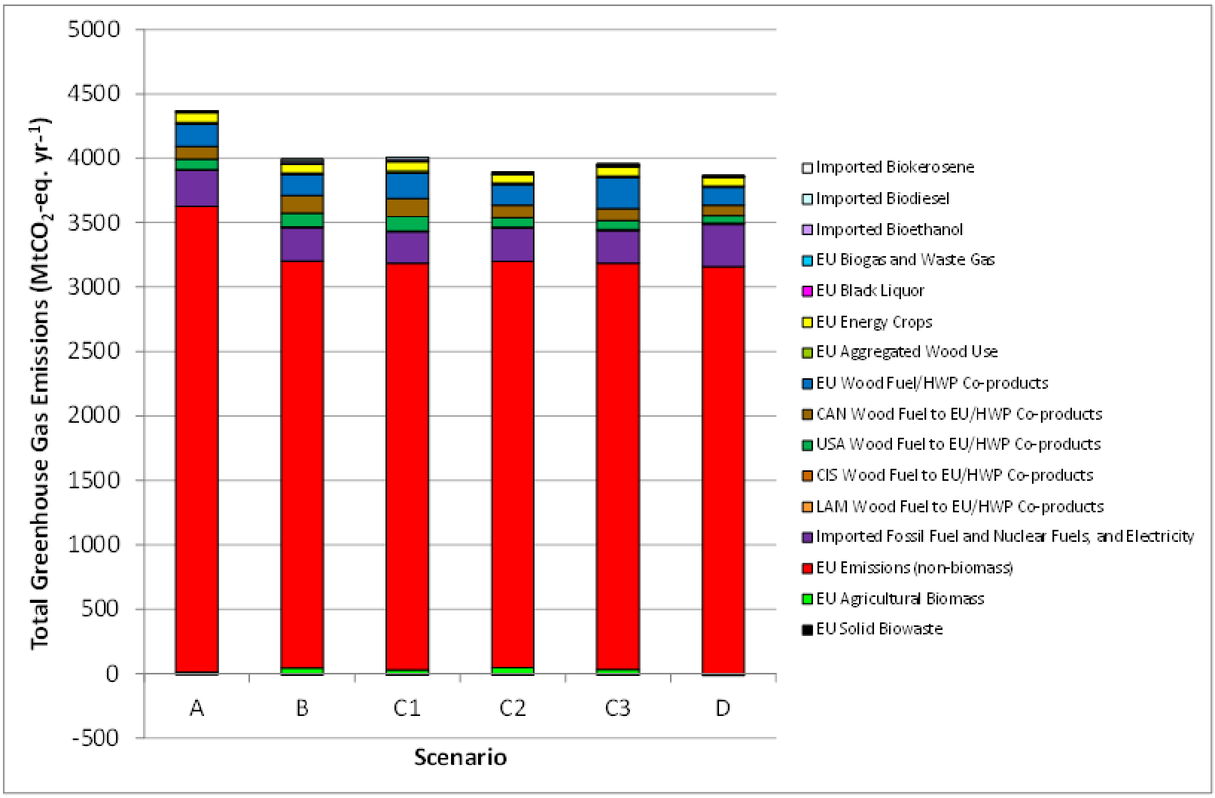

Figure 6.3a. Final project results for all scenarios for the year 2030, showing contributions from various sources to total annual GHG emissions. Results have been calculated using average emissions factors and refer to the Precautionary' approach to forest management and wood use.

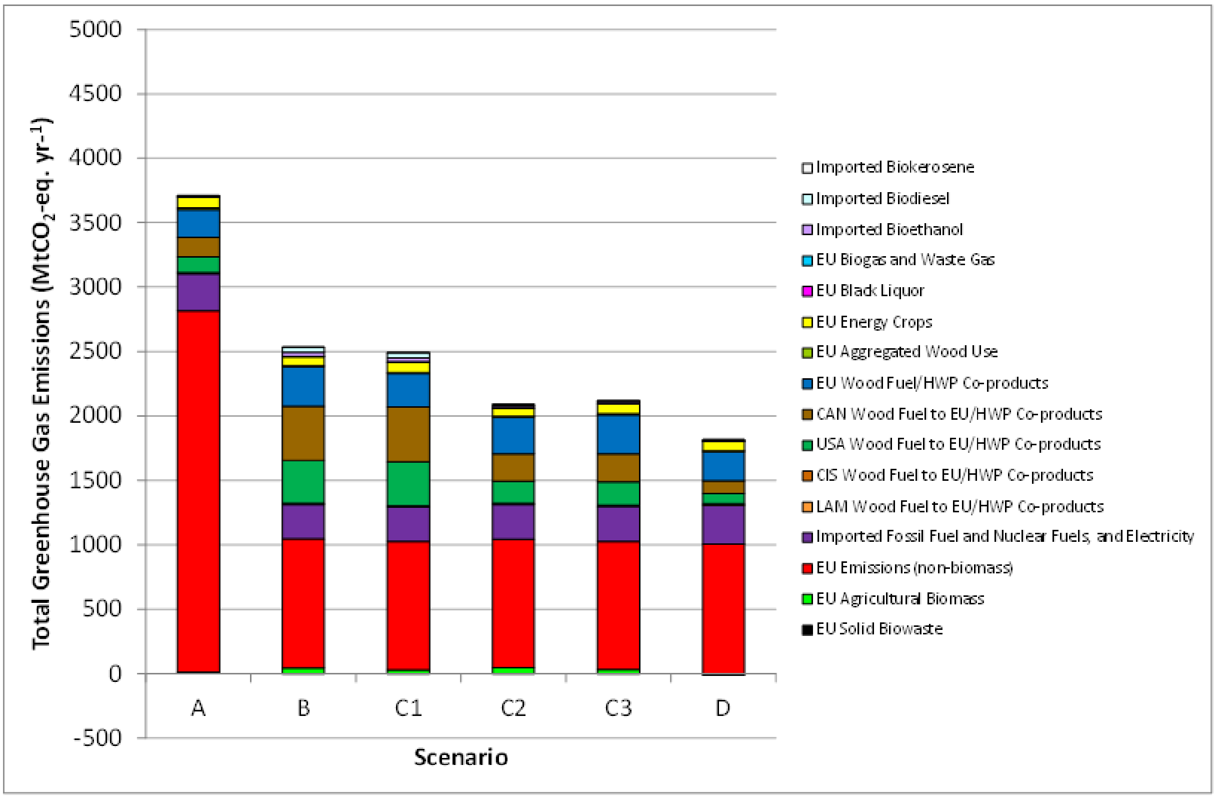

Figure 6.3b. Final project results for all scenarios for the year 2050, showing contributions from various sources to total annual GHG emissions. Results have been calculated using average emissions factors and refer to the Precautionary' approach to forest management and wood use.

A quantitative assessment of the results in Figure 6.3a, identifying for each scenario the main contributions to total GHG emissions, and associated reductions and increases, is shown in Tables 6.2 and 6.3.

Table 6.2 shows, in summarised form, the contributions to total annual GHG emissions in 2030, as estimated for each of the scenarios developed in this project. Results are given for three aggregated categories of GHG emissions (based on the more detailed categories described in Section 6.4):

1. 'Fossil' (essentially the GHG emissions reported as "EU emissions (non-biomass)")
2. 'Bioenergy' (consisting of the sum of key contributions associated with bioenergy sources, specifically, the categories, "Agricultural biomass", "Energy crops" and the various categories of "Wood Fuel/HWP Co-products")
3. 'Other' (consisting of the sum of contributions for all other categories, notably "Imported Fossil Fuel and Nuclear Fuels, and Electricity").

Table 6.2 Summary of key contributions to total annual GHG emissions in 2030 by scenario

Scenario	GHG emissions ($MtCO_2$-eq. yr^{-1})			
	Fossil	Bioenergy	Other	Total
A (Reference)	3 615	448	295	4 358
B ('Carry on/ unconstrained use')	3 159	524	296	3 980
C1 ('Carry on/ imported wood')	3 158	556	284	3 997
C2 ('Carry on/ domestic crops')	3 155	447	277	3 880
C3 ('Carry on/ domestic wood')	3 155	512	276	3 943
D ('Back off')	3 162	353	335	3 850

A number of key features may be discerned from Table 6.2 concerning the contributions of GHG emissions due to key categories to the total annual GHG emissions in 2030:

- The contribution due to 'Fossil' GHG emissions under the Reference Scenario A is estimated at 3 615 $MtCO_2$ yr^{-1}, whilst equivalent results for the decarbonisation scenarios are lower, at between 3 155 and 3 162 $MtCO_2$ yr^{-1}.
- The contributions due to 'Bioenergy' GHG emissions under the Reference Scenario A are estimated at 448 $MtCO_2$ yr^{-1}, whilst the equivalent estimates for the decarbonisation scenarios exhibit some variation. For the 'Back off' Scenario D, the estimated GHG emissions due to 'Bioenergy' are lower, at 353 $MtCO_2$ yr^{-1}, whereas results for the various 'Carry on' Scenarios are generally higher than for Reference Scenario A, ranging between 512 and 556 $MtCO_2$ yr^{-1}, with the exception of Scenario C2, for which 'Bioenergy' GHG emissions are very similar to Scenario A.
- The contributions due to 'Other' GHG emissions under Reference Scenario A are estimated at 295 $MtCO_2$ yr^{-1}.Equivalent estimates for the various 'Carry on' Scenarios are similar, ranging between 276 and 297 $MtCO_2$ yr^{-1}, whereas the result for the 'Back off' Scenario D is higher, at 335 $MtCO_2$ yr^{-1}.

It is apparent from the results in Table 6.2 that increases in GHG emissions due to 'Bioenergy' under the 'Carry on' Scenarios, compared with Reference Scenario A, are outweighed by reductions in GHG emissions in the 'Fossil' category. The comparison of the results in Table 6.2 for the various decarbonisation scenarios, with those for Reference Scenario A, may be further clarified by considering differences in contributions to GHG emissions relative to the results for Scenario A, as shown in Table 6.3.

Table 6.3 Summary of changes in key contributions to total annual GHG emissions in 2030, by scenario, relative to Reference Scenario A

Scenario	GHG emissions ($MtCO_2$-eq. yr^{-1})			
	Fossil	**Bioenergy**	**Other**	**Total**
B ('Carry on/ unconstrained use')	-456	77	2	-378
C1 ('Carry on/ imported wood')	-458	108	-11	-360
C2 ('Carry on/ domestic crops')	-460	0	-17	-478
C3 ('Carry on/ domestic wood')	-460	64	-18	-415
D ('Back off')	-454	-95	41	-508

The results in Table 6.3 reveal that:

- For all of the decarbonisation scenarios, there is a similar and significant reduction in the contribution to total annual GHG emissions due to 'Fossil' GHG emissions, relative to Reference Scenario A, of between 454 and 460 $MtCO_2$ yr^{-1}.
- The changes in the contributions to total annual GHG emissions due to 'Bioenergy' emissions in the decarbonisation scenarios, compared with Reference Scenario A, are variable. For the 'Back off' Scenario D, the contribution is reduced by 95 $MtCO_2$ yr^{-1}, reflecting the lower use of bioenergy under this scenario after 2020, due to its deprioritisation. In contrast, the contributions due to 'Bioenergy' are generally increased under the 'Carry on' Scenarios, by up to 108 $MtCO_2$ yr^{-1}, being highest for Scenario C1 ('Carry on/imported wood'). A notable exception is Scenario C2 ('Carry on/domestic crops'), which shows no change in the contribution due to this category in 2030, relative to the Reference Scenario A. This reflects several factors, such as the emphasis on agricultural sources of bioenergy in Scenario C2. However, a key reason for the negligible change in 'Bioenergy' GHG emissions is due to the projected level of forest bioenergy use in 2030 being almost the same in Reference Scenario A and Scenario C2, whilst the level of forest bioenergy use in 2030 is higher in the other 'Carry on' Scenarios.
- For all the decarbonisation scenarios, changes in GHG emissions relative to Reference Scenario A in the category 'Other' are smaller than for the 'Fossil' and 'Bioenergy' categories. However, a small but significant increase in 'Other' GHG emissions may be noted for Scenario D ('Back off'). This is mainly the result of increased emissions relative to Reference Scenario A in the detailed category of "Imported Fossil Fuel and Nuclear Fuels, and Electricity".

A qualitative assessment of the results in Figure 6.3b, identifying the main sources of reductions and increases in total GHG emissions for each scenario in 2050, is shown in Table 6.4.

A number of specific features can be determined from the results for 2050 in Figure 6.3b.

For all scenarios, GHG emissions, including biogenic carbon emissions, associated with increased use of agricultural sources of bioenergy (produced within the EU27 region, see categories "EU Agricultural Biomass" and "EU Energy Crops" in Figure 6.3b), associated *with increased use are consistently low, compared with fossil energy sources. However, as explained in Section 4.9.4, significant variations in GHG emissions for specific agricultural biomass sources should be noted. In particular, the establishment of energy crops in the EU, as represented in the scenarios, generally leads to carbon sequestration. Conversely, the removal of agricultural residues, notably straw, leads to increased biogenic carbon emissions.*

For the Reference Scenario A, contributions to GHG emissions due to forest bioenergy (across the various categories of "Wood Fuel/HWP Co-Products" in Figure 6.3b) are significantly smaller, compared with the various 'Carry on' Scenarios. This reflects the assumption in Scenario A that more ambitious targets for renewable energy consumption and reductions in GHG emissions will not be set for the period post 2020. The lower consumption of renewable energy in Scenario A also involves less displacement of GHG emissions from fossil energy sources, compared with the decarbonisation scenarios. Consequently the contribution to GHG emissions due to the category, "EU Emissions (non-biomass)", as shown in Figure 6.3b, is significantly greater than for the other scenarios.

Table 6.4 Summary assessment of sources of reductions and increases in contributions to total annual GHG emissions for scenarios

Scenario	Sources of GHG emissions reductions and increases
A ('Reference')	Reduction in EU emissions (non-biomass) Smaller increases in emissions from Canadian, US and EU wood fuel/HWP co-products
B ('Carry on/unconstrained use')	Significant reduction in EU emissions (non-biomass) Significant increase in emissions from Canadian and US wood fuel/HWP co-products. Significant but smaller increases in emissions from EU wood fuel/HWP co-products. Significant but smaller increase in emissions from EU agricultural biomass.
C1 ('Carry on/imported wood')	Significant reduction in EU emissions (non-biomass) and imported fossil and nuclear fuels and electricity Significant increases in emissions from Canadian, US and EU wood fuel/HWP co-products. Significant but smaller increase in emissions from EU agricultural biomass.

Table 6.4 (continued) Summary assessment of sources of reductions and increases in contributions to total annual GHG emissions for scenarios

Scenario	Sources of GHG emissions reductions and increases
C2 (‘Carry on/domestic crops’)	Significant reduction in EU emissions (non-biomass) Significant but smaller increase in emissions from EU agricultural biomass. Significant but smaller increases in emissions from Canadian, US and EU wood fuel/HWP co-products.
C3 (‘Carry on/domestic wood’)	Significant reduction in EU emissions (non-biomass) Significant but smaller increases in emissions from Canadian, US and EU wood fuel/HWP co-products. Significant but smaller increase in emissions from EU agricultural biomass.
D (‘Back off’)	Significant reduction in EU emissions (non-biomass) Smaller increases in emissions from Canadian, US and EU wood fuel/HWP co-products Significant but smaller increase in emissions from expanded use of nuclear power, and imported natural gas, nuclear fuel and electricity.

Scenario B (‘Carry on/unconstrained use’) displays the greatest increases in contributions to total annual GHG emissions due to the consumption of bioenergy. The increase occurs for all sources of bioenergy, reflecting the unconstrained nature of the scenario. In particular, there are relatively high contributions due to the consumption of imported forest bioenergy (see discussion of Scenario C1 below).

Scenario C1 (‘Carry on/imported wood’) is similar to Scenario B in terms of increases in contributions to total annual GHG emissions due to the consumption of bioenergy. The main increases are in the contributions due to consumption of forest bioenergy imported from Canada and the USA, reflecting the definition of the scenario. It is notable across all scenarios that GHG emissions associated with forest bioenergy imported from Canada and the USA are generally higher than those associated with forest bioenergy produced domestically in the EU region. A preliminary analysis based on very approximate biogenic carbon emissions factors for forest bioenergy sources (see Section 4.10.6) has already highlighted the contrasts in results, particularly for Canada and the EU. This is due to a number of factors including, for example, contrasting growth rates of forests in Canada, the USA and the EU region, and differences in approaches to forest management in these regions under a business as usual scenario, and also in response to increased demand for forest bioenergy (see Section 4.8.4). Section 6.7 includes a more detailed discussion of the distinctions in assumptions underlying the modelling of scenarios for forest bioenergy supply to the EU27 region, from domestic production within the EU27 region, and from wood imported from Canada and the USA, and also considers the implications for the consequent estimates of GHG emissions associated with these sources of forest bioenergy. Despite the increases in total annual GHG emissions in Scenarios B and C1 due to contributions from forest bioenergy, particularly imported forest bioenergy, overall, total annual GHG emissions decrease significantly, because of the greatly reduced contribution from consumption of fossil fuels, i.e. due to the category, "EU Emissions (non-biomass)". However, as already highlighted in the discussions in Sections 6.4.1 and 6.5.1, the projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. As a consequence, the contribution made specifically by bioenergy to net changes in GHG emissions over time is difficult to discern from overall results for total annual GHG emissions. This has been partially addressed by the preceding assessment, but further, detailed analysis of the specific contributions due to forest bioenergy, is also presented in Sections 6.7 and Section 6.9.

Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood') have lower associated total annual GHG emissions, compared with Scenarios B and C1. This reflects the emphasis in both Scenarios C2 and C3 on domestic bioenergy production, and consequently lower dependence on imported (forest) bioenergy. The total annual GHG emissions for Scenarios C2 and C3 are very similar in magnitude. There are small differences in the contributions to GHG emissions due to agricultural biomass (slightly higher for Scenario C2) and due to forest bioenergy produced domestically in the EU region (slightly higher for Scenario C3).

Total annual GHG emissions in 2050 are lowest for Scenario D ('Back off'). By the nature of the definition of the scenario, consumption of bioenergy post 2020 is lowest, and associated increases in contributions to GHG emissions due to bioenergy sources are the smallest amongst the scenarios. However, the results from Task 2 for Scenario D suggest that de-prioritising biomass consumption for energy in the EU post-2020, whilst also trying to achieve significant reductions in GHG emissions would involve:

- The increased use of other renewable energy sources (particularly solar and wind power)
- More concerted efforts towards energy efficiency in the EU region, notably in the residential and transport sectors
- Increased use of nuclear power
- Some increased deployment of carbon capture and storage technologies.

This would also involve increased reliance on natural gas, nuclear fuels and electricity imported into the EU region from elsewhere. This is reflected in a slightly higher contribution to total annual GHG emissions due to the category, "Imported Fossil Fuel and Nuclear Fuels, and Electricity".

The implications of the actions required to fulfil the outcomes of Scenario D, compared with the various 'Carry on' Scenarios, are not fully apparent from consideration of the detailed results for GHG emissions in Figures 6.3b. This is because a number of the impacts for Scenario D are more to do with non-biomass energy sources, and issues related to security of energy supply.

6.6.1. Impacts on GHG emissions due to high forest bioenergy use post 2030

In addition to the preceding analysis, a further feature of the results for the various 'Carry on' Scenarios should be highlighted. The results in Figures 6.2, 6.3a, 6.3b and Table 6.1 indicate that, at some point between 2030 and 2050, projected total annual GHG emissions for the various 'Carry on' Scenarios may be starting to diverge from the trajectory for the 'Back off' Scenario D. Total annual GHG emissions for Scenario D decline at a broadly consistent rate over the period 2030 to 2050. However, the rate of decline is similar for the 'Carry on' Scenarios over the period 2030 to 2040, but less pronounced than for Scenario D over the period 2040 to 2050. This is particularly apparent in the trajectories of total annual GHG emissions in Figure 6.2. It is important to understand the reason for the less rapid rate of decline in total GHG emissions for the 'Carry on' Scenarios, which, essentially, is related to the projected levels of forest bioenergy consumption, as modelled in Task 2. As explained in the discussion of the development of forestry scenarios in Section 4.8.2, the 'Carry on' Scenarios all involve a pronounced increase in estimated consumption of forest bioenergy at some point after 2030, up to 2050, relative to the period up to 2030. The effect on total annual GHG emissions by 2050 is apparent in Figure 6.3b, in terms of increases in the contributions made by the various categories of "Wood Fuel/HWP Co-products". This effect is far less apparent in the results for 2030 (before the pronounced increases in forest bioenergy consumption occur in the 'Carry on' Scenarios), as shown in Figure 6.3a.

The pattern of results observed for the 'Carry on' Scenarios over the period from 2030 to 2050 is largely the result of projected increases in forest bioenergy consumption, starting from some point after 2030. The analysis of forest bioenergy scenarios with respect to long-term potential sustainable-yield wood supply in Section 4.9.2 highlighted that the levels of forest bioenergy supply set for 2050 in some scenarios approach an upper limit for sustainable-yield supply.

The relationship between the trend in increasing forest bioenergy consumption represented in the various 'Carry on' Scenarios, and the consequences for biogenic carbon emissions, has already been discussed in Section 4.10.6. In that discussion, the possibility was suggested for allowing the level of supply of forest bioenergy to increase, but only up to 2030, or possibly 2040, and then constraining levels of supply not to increase further from that point. It was further suggested that an even more refined approach might be possible, for example allowing the supply of some forest bioenergy sources to increase only up to 2020, some to increase to 2030 and others up to 2050. The modelling of such refined scenarios could be a subject for further research.

It follows that any targets for future levels of forest bioenergy supply need to be set with care, with particular regard to potentials for sustainable-yield supply. Furthermore, increases in the consumption of forest bioenergy should be phased in over appropriate timescales that do not lead to pulses in CO_2 emissions.

6.6.2. Conclusions on sources of changes in total annual GHG emissions

Based on the above assessment of total annual GHG emissions for the years 2030 and 2050, the following conclusions may be drawn.

The relatively smaller reductions in total annual GHG emissions for the Reference Scenario A, compared with the decarbonisation scenarios, reflects the fact that more ambitious targets post 2020 for renewable energy consumption and reductions in GHG emissions would not be set under Scenario A. Consequently, GHG emissions due to fossil fuel consumption are significantly greater for Scenario A than for the other scenarios.

For the various 'Carry on' Scenarios, representing situations in which supply and consumption of bioenergy increases in the EU region, contributions to GHG emissions due to bioenergy sources, particularly forest bioenergy sources, are increased compared with Reference Scenario A. However, these increases are small relative to total annual GHG emissions and are outweighed by significant reductions in GHG emissions due to the reduced consumption of fossil fuels. It is, nevertheless, important to note that the projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. As a consequence, the contribution made specifically by bioenergy to net changes in GHG emissions over time is difficult to discern from overall results for total annual GHG emissions. This has been partially addressed by the preceding assessment, but further, detailed analysis of the specific contributions due to forest bioenergy, is also presented in Sections 6.7 and Section 6.9.

Relatively small systematic differences between the results for the scenarios can be identified, in terms of changes in contributions due to GHG emissions from sources related to the definitions of the scenarios. In particular, scenarios involving relatively significant importation of forest bioenergy achieve smaller reductions in total annual GHG emissions in 2030 and 2050, due to contributions to GHG emissions from these sources. The 'Back off' Scenario D involves the lowest consumption of bioenergy post 2020 and thereby avoids increases in contributions of GHG emissions from bioenergy sources. However, there are small increases in contributions to GHG emissions due to consumption of other energy sources.

There is some evidence from the modelling of forestry in Task 3 that the projected levels of forest bioenergy supply under the 'Carry on' Scenarios approach an upper limit for sustainable-yield supply from 2030, particularly in the EU region. The pronounced increase in forest bioenergy supply from some point after 2030 up to 2050, as represented in the 'Carry on' Scenarios, also leads to a response in the contributions to total annual GHG emissions from forest bioenergy sources in 2050. Any targets for future *levels and rates of increase in forest bioenergy supply need to be set with care, with particular regard to potentials for sustainable-yield supply and time-dependent impacts on biogenic carbon emissions.*

6.7. Sensitivity to approaches to forest management and wood use

6.7.1. Sensitivity in results for different supplying regions

The final project results indicate that the GHG emissions associated with forest bioenergy sources are sensitive to assumptions about approaches to forest management and wood use that are involved in increasing levels of supply. An important aspect of such sensitivities has already been identified in Section 6.6, specifically, that GHG emissions associated with forest bioenergy sources imported to the EU from Canada and the USA are higher than for forest bioenergy sources produced domestically in the EU27 region. As already noted in Section 6.6, this is due to a number of factors, including:

- Contrasting growth rates of forests in Canada, the USA and the EU region
- Differences in approaches to forest management in these regions under a business as usual scenario, and also in response to increased demand for forest bioenergy
- Differences in patterns in the production and use of wood associated with the increased supply of forest bioenergy (including material wood co-products).

As explained in Section 3.10 of the Task 1 report for this project (Matthews *et al.*, 2014a), the growth rate of forests is a key factor in determining biogenic carbon emissions associated with wood production. Rough estimates of the mean growth rates of forests in the EU27 region, Canada and the USA are given in Section 2.4.2 of the Task 1 report (*op. cit.*), respectively at 6, 4 and 6 m^3 ha^{-1} yr^{-1}. The lower growth rates of forests in Canada will be one cause of higher estimates of GHG emissions associated with forest bioenergy supply from Canada to the EU. However, one of the most important ways in which growth rate will cause differences in GHG emissions is through its influence on decisions about approaches to the management of forest areas (see Section 4.8.4).

The main reasons for differences in GHG emissions estimated for forest bioenergy supplied from different regions to the EU are related to the assumptions made in modelling the approaches to forest management and wood use involved in increasing levels of forest bioenergy supply in different geographical regions. These assumptions, and their implications for the modelling of forest management changes, have been explained in detail in Section 4.8.4, and the key differences for different regions have been discussed in Section 4.10.1. Notably:

- For all regions external to the EU, including Canada and the USA, the increased supply of forest bioenergy to the EU region is simulated to involve a significant contribution due to the introduction of management for production in areas where currently this is not taking place. This is particularly the case for Canada.
- For the EU27 region, the increased extraction of wood for bioenergy in forest areas already under management for production is projected to make a much more important contribution to forest bioenergy supply, compared to the results for imported wood.

These differences in emphasis on the types of forest management represented in different regions have consequences for resultant estimates of biogenic carbon emissions associated with wood harvesting. In particular, often, the introduction of management for production, in areas where currently this is not taking place, will involve felling in mature forest stands (see Box 4.2, Section 4.8.4), which have accumulated high carbon stocks (in trees, litter and soil). For this reason, the impacts of harvesting on carbon stocks in these stands are, potentially, greater than is the case where forest bioenergy production involves increased extraction of biomass from stands that are already under management for production (see Sections 3.6.2 and 3.6.3 of the Task 1 report for this project for illustrations).

It is also important to note that the biogenic carbon emissions associated with the harvesting of forest areas are strongly affected, in some scenarios, by a pronounced increase in the projected level of forest bioenergy supply, at some point after 2030 up to 2050, for scenarios involving higher levels of imported forest bioenergy (see discussion of Figures 4.13 to 4.16 in Section 4.8.2). As discussed in Section 6.6, this projected increase in forest bioenergy use leads to a less rapid decline in total annual GHG emissions after 2030, particularly when compared with Scenario D ('Back off'). The implications of this feature of the 'Carry on' Scenarios, especially those involving higher levels of imported wood, have been discussed in Section 6.6.

The differences in forest management approaches represented in different supplying regions also have consequences for patterns of wood use, both for bioenergy and for material wood products. The analysis in Section 4.9.2 highlighted that the main contributions to forest bioenergy supply from the EU27 region were due to small roundwood (in large part in the form of small trees) and harvest residues. In contrast, the main contributions to forest bioenergy supply from Canada were due to sawmill co-products. Co-production of material wood products in conjunction with forest bioenergy production was also more significant for Canada than for the EU27 region. The pattern exhibited in results for the USA are a combination of those for the EU27 region and Canada; specifically, the main contributions to forest bioenergy supply are due to small roundwood and harvest residues, whilst co-production of material wood products alongside forest bioenergy is also significant.

The different patterns in types of harvested wood used as feedstock for bioenergy can be illustrated by considering the quantities of forest bioenergy supplied to the EU27 region from within the EU27 region, from Canada and from the USA, in the year 2030. The relative contributions due to sawmill co-products on the one hand, and other wood sources (i.e. small roundwood, harvest residues and bark) on the other hand, are very similar for all the scenarios developed in this project:

- For the supply of forest bioenergy from the EU27 region, sawmill co-products contribute about 20% of the total supply
- For the supply of forest bioenergy from Canada, sawmill co-products typically contribute slightly more than 50% of the total supply

- For the supply of forest bioenergy from the USA, sawmill co-products typically contribute about 25% of the total supply.

These results reflect the underlying assumptions about forest management in these supplying regions, as discussed earlier. In particular, the differences in the relative contributions made by sawmill co-products are related to the extent to which forest bioenergy is increased through the introduction of management for production in areas where currently this is not taking place. This is because, generally, this forest management approach is assumed to involve co-production of forest bioenergy with at least some material wood products (i.e. sawn wood, under the 'Precautionary' approach, see Table 4.9, Section 4.8.3).

The assumptions made about forest management associated with increased forest bioenergy supply from within the EU27 region, from Canada and from the USA lead to contrasting interactions with the supply of harvested wood for use as material wood products. These differing interactions have an important bearing on the final results for the 'high import' Scenarios B and C1, and the 'high domestic supply' Scenarios C2 and C3, in terms of total annual GHG emissions. The interactions are illustrated in Figure 6.4, which shows how levels of forest bioenergy supply from the EU27 region, Canada and the USA vary for Scenarios B, C1, C2 and C3, in the year 2030. The figure also shows the associated marginal levels of wood supply (i.e. the changes in levels of wood supply relative to the baseline scenario) in 2030, for use as material wood products.

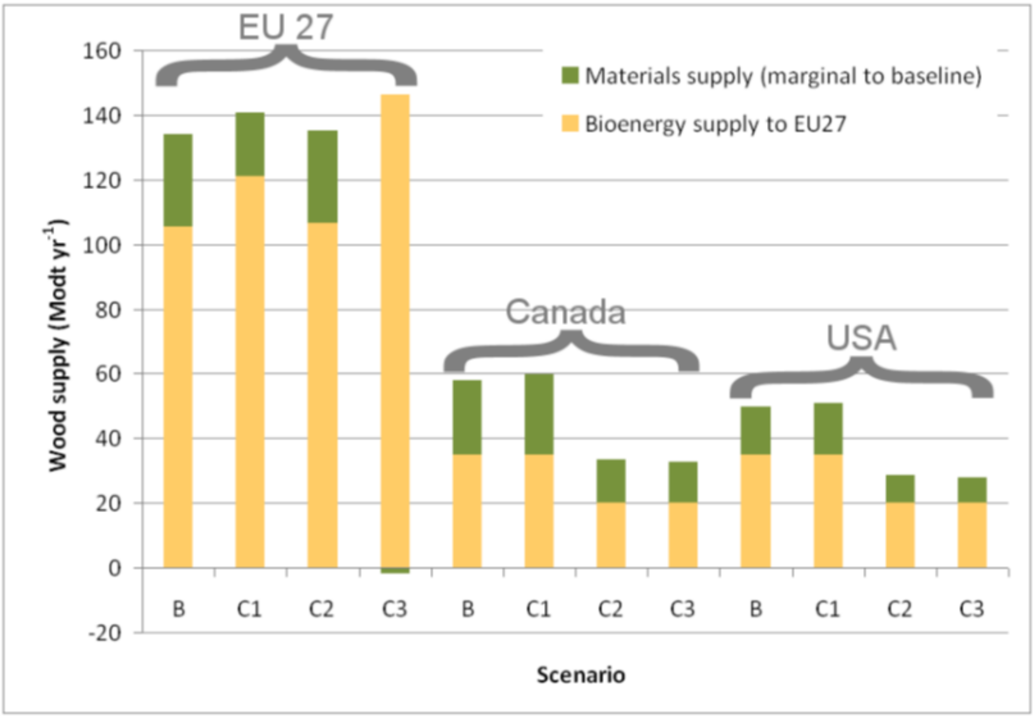

Figure 6.4. Comparison of levels of wood supply to the EU27 region, from within the EU27 region, and from Canada and the USA, for the year 2030, as represented in Scenarios B, C1, C2 and C3. Results have been calculated by referring to 'Precautionary' approach to forest management and wood use.

Some important features are apparent in the results in Figure 6.4, specifically:

- For Canada and the USA, the levels of forest bioenergy supply to the EU27 region are greatly increased under Scenarios B and C1, compared with Scenarios C2 and C3.
- For the EU27 region, the levels of forest bioenergy (domestic) supply vary between the individual scenarios. The levels of supply are lowest (and similar) for Scenarios B and C2, in which a relatively large proportion of the requirements for bioenergy in the EU27 region (as determined by the VTT-TIAM model in Task 2) are met by agricultural production and the importation of forest bioenergy (mainly from Canada and the USA). The level of forest bioenergy supply is highest in Scenario C3, which is to be expected for a scenario emphasising domestic production of forest bioenergy. For Scenario C1, the level of forest bioenergy supply from the EU27 region is slightly higher than for Scenarios B and C2.
- For Canada and the USA, the increased levels of forest bioenergy supply to the EU27 region under all scenarios are accompanied by increased supplies of wood for material wood products, due to co-production (see earlier). The level of co-production rises with the level of forest bioenergy supply (based on comparison of the results in Figure 6.4 for Scenarios B and C1, with those for Scenarios C2 and C3).
- For the EU27 region, the increased levels of forest bioenergy supply in Scenarios C1 and C3 (compared with Scenarios B and C2) are achieved, partly or wholly, through the diversion of harvested wood from use for material wood products. This is apparent in Figure 6.4 from the reduced magnitude of the result for the marginal supply of wood for materials for Scenario C1, compared with Scenarios B and C2. The outcome is pronounced for Scenario C3, in which the marginal supply of wood for use as material wood products is slightly negative, implying a slight reduction in the overall level of supply of material wood products, compared to the baseline scenario.

It follows that the higher GHG emissions associated with scenarios involving relatively high levels of supply of forest bioenergy from imported sources, notably from Canada and the USA, are partly a consequence of associated interactions between the supply of forest bioenergy and the supply of harvested wood for material wood products, specifically involving increased co-production. This contrasts to the scenario for forest bioenergy supplied from within the EU27 region, which involves the diversion of wood from use for materials to use as bioenergy[11]. This outcome may seem to contradict the findings of studies that have suggested that the co-production of forest bioenergy in conjunction with material wood products leads to net reductions in overall GHG emissions, whilst the diversion of wood supplies, from use for materials to use as bioenergy, generally leads to net increases in overall GHG emissions (Matthews *et al.*, 2014b). However, the results of these studies also show that the impacts on GHG emissions associated with co-production of forest bioenergy and material wood products are very sensitive to the specific combination of co-products and end uses involved in a particular scenario. Furthermore, whilst the co-production of material wood products alongside increased forest bioenergy production can have positive impacts on GHG

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[11] It should be noted that the interactions are quite complicated for the EU27 region. Overall, wood is diverted from use for materials to use as bioenergy. However, the underlying changes for different categories of material wood product are variable, and may increase or decrease, and also vary in terms of interactions over time. An illustration of these detailed changes, as modelled for the EU27 region, is given Figure 4.31, Section 4.10.3, based on results for Reference Scenario A.

emissions, this may also have negative impacts when wood products are disposed of at end of life. This is particularly the case if efforts are not made to ensure the disposal of wood products occurs with low carbon impacts (see for example Matthews *et al*., 2014b). This issue is explored further in Section 6.7.3. These issues also need to be considered when assessing the potential impacts of diverting wood from use as a material to use as bioenergy.

The estimated impacts on GHG emissions associated with the increased supply of forest bioenergy, from either external or domestic EU27 sources, are also sensitive to assumptions about the counterfactuals for material wood products and the choice of GHG emissions factors used in calculating the final results. It is important to note that the main final project results, in terms of total annual GHG emissions over time for each of the scenarios developed in this project, have been calculated using average emissions factors, as explained in Section 6.3.1.

As explained in Section 6.3.1, the application of average GHG emissions factors in calculating the main final project results is an appropriate approach, but involves assumptions with regard to the utilisation of material wood co-products that are not optimised to achieve reductions in GHG emissions. The sensitivity of GHG impacts associated with forest bioenergy use, due to interactions with the supply of material wood products (including the potential for measures to promote the effective use of material wood co-products to achieve overall reductions in GHG emission), is explored further in Section 6.7.3.

In conclusion, the 'Carry on' Scenarios modelled in this project indicate that GHG emissions associated with scenarios involving higher use of forest bioenergy sources produced externally to the EU, particularly imports to the EU from Canada and the USA, are higher than for scenarios that emphasise forest bioenergy produced domestically within the EU27 region because of differences in assumptions about the growth rates of the forests involved, forest management approaches, subsequent biogenic carbon emissions, types of feedstock for forest bioenergy, interactions with material wood products and their associated counterfactuals, and end-of-life disposal pathways for material wood products.

It is important to appreciate that there is an intimate linkage between the outcomes reported as the main results of this project in Sections 6.4 to 6.6, and the underlying assumptions highlighted above. The sensitivities in the final results for total annual GHG emissions to assumptions about approaches to forest management and the utilisation of wood are explored further in Sections 6.7.2 and 6.7.3.

6.7.2. Sensitivity to forest management approaches

The final project results may be examined in further detail, to investigate the potential sensitivity of outcomes for the scenarios developed in this project, in terms of total annual GHG emissions, to assumptions about forest management approaches involved in increasing the supply of forest bioenergy. Such an investigation may also offer insights into how forest management might be influenced to ensure more positive outcomes in terms of the GHG impacts of increased forest bioenergy supply. As explained in Section 6.3.1, the modelling of forest management and patterns of wood use involved in the supply of forest bioenergy has considered two possible approaches:

1. The 'Precautionary' approach was designed to represent a plausible set of changes in forest management and wood use to supply increased quantities of forest bioenergy in the EU. This involves assumptions that imply the discouragement or avoidance of some (but not all) higher risk options for production of forest bioenergy.
2. The 'Synergistic' approach involves assumptions that imply that actions take place that go beyond those of the 'Precautionary' case. Such actions include approaches to forest management that should ensure more rapid recovery of carbon stocks after harvesting, and the active conservation and enhancement of forest carbon stocks alongside increased harvesting to produce forest bioenergy.

In addition, co-production of material wood products alongside production of forest bioenergy is strongly emphasised in the 'Synergistic' approach, compared with the 'Precautionary' approach.

The assessment of the final project results has focused on results based on the 'Precautionary' approach to forest management and wood use. This is because this approach was identified as most relevant to refer to when calculating the main project results (see Section 6.3.1). In Figure 6.5, an assessment is made of the potential impacts of the further positive actions with regard to forest management and wood use, as considered under the 'Synergistic' approach. For reasons explained in the ensuing discussion, the results in Figure 6.5 mainly illustrate effects on the carbon dynamics of forests in response to their management, with secondary effects on GHG emissions associated with possible end uses of harvested wood.

Figure 6.5 shows the magnitudes of the contributions to overall results in the year 2050 for each scenario, as made by the various categories of GHG emissions sources listed in Section 6.4. Two sets of results have been calculated, referring respectively to the 'Precautionary' and 'Synergistic' approaches to forest management and wood use. The variable contributions due to different categories are apparent in Figure 6.5.

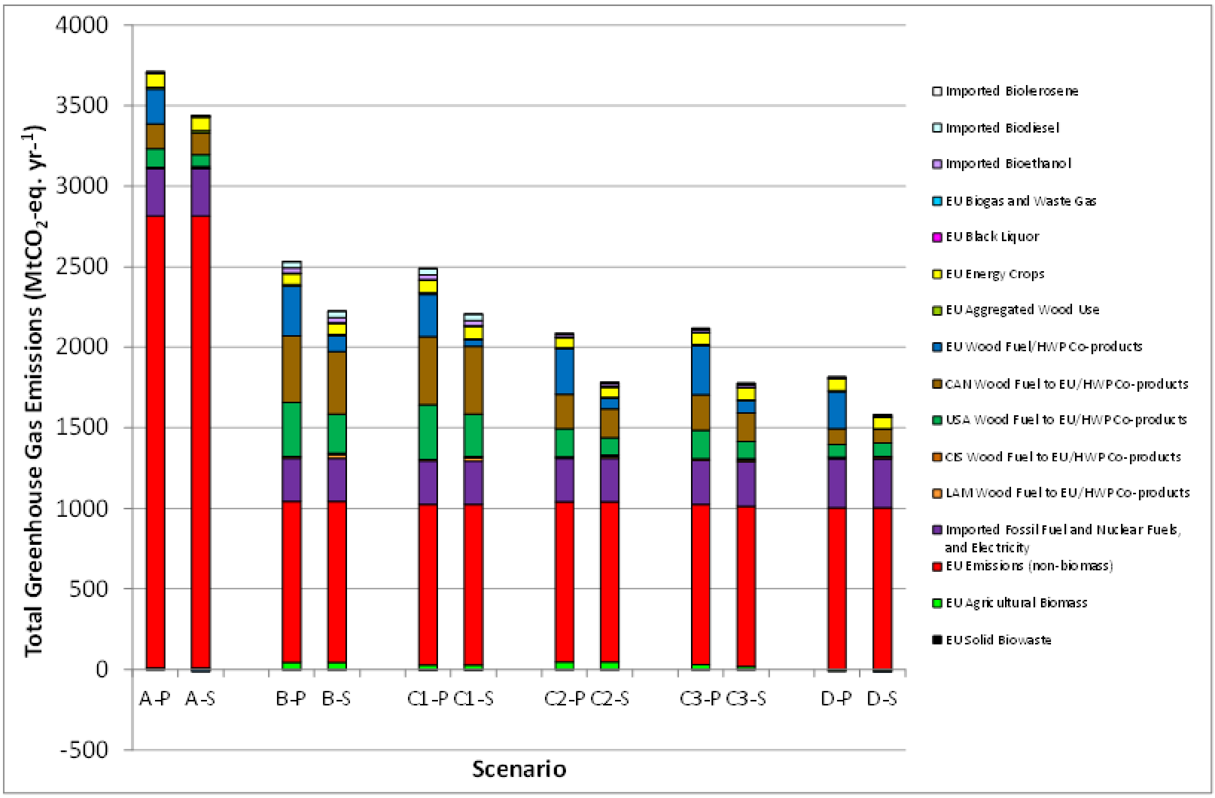

Figure 6.5. Total annual GHG emissions for all scenarios for the year 2050, showing contributions from various sources. Results have been calculated using average emissions factors and referring to either the Precautionary' approach ('-P') or the 'Synergistic' approach ('-S') to forest management and wood use.

It is evident from Figure 6.5 that, invariably, for the 'Synergistic' approach in comparison with the 'Precautionary' approach, the total annual GHG emissions in 2050 are reduced for all scenarios. The extent of this reduction shows small variations and is most pronounced for Scenario C3 ('Carry on/domestic wood'). For all scenarios, the biggest reduction in the contribution to total annual GHG emissions under the 'Synergistic' approach is associated with the category, "EU Wood Fuel/HWP Co-products". This reflects the fact that the major changes in assumptions about forest management for the 'Synergistic' approach involve forests in the EU27 region. These changed assumptions involved:

- Enhanced rates of afforestation in most EU Member States post 2015 (see Section 4.7.2)
- Actions to improve the growing stock of forests, thereby conserving or enhancing forest carbon stocks in conjunction with increased forest bioenergy supply (see Section 4.8.3).

In contrast, for Canada, assumptions about rates of afforestation and approaches to forest management were the same for the 'Precautionary' and 'Synergistic' approaches. For the USA, assumptions about rates of afforestation were also the same for the 'Precautionary' and 'Synergistic' approaches, whilst the potential for actions to improve the growing stock of forests was assumed to be quite limited. The main change in assumptions about imported forest bioenergy for the 'Synergistic' approach, compared with the 'Precautionary' approach, involved the inclusion of a contribution to forest bioenergy supply from fast growing forest plantations in the LAM region (i.e. specifically in Brazil), dedicated to forest bioenergy production (see Section 4.8.3). This also had the effect of reducing the magnitudes of the contributions made by forest bioenergy supplied to the EU region from Canada and the USA under the 'Synergistic' approach.

Figure 6.5 also shows that the contributions to total annual GHG emissions due to the categories, "CAN Wood Fuel to EU/HWP Co-products" and "USA Wood Fuel to EU/HWP Co-products" are reduced under the 'Synergistic' approach, compared with the 'Precautionary' approach. However, the reductions are quite modest, compared with forest bioenergy supplied from within the EU27 region. This is particularly the case for forest bioenergy supplied from Canada, for which no potential was assumed for additional positive actions with regard to forest management, including afforestation. The main reason for the reduction in the contributions to total annual GHG emissions associated with forest bioenergy supplied from Canada and the USA, under the 'Synergistic' approach, is simply due to the fact that less bioenergy is being supplied from these sources, compared with the 'Precautionary' approach, as a result of the contributions made by forest bioenergy supplied from Brazilian plantations.

As illustrated in Section 4.10.6, the GHG emissions due to biogenic carbon associated with forest bioenergy production from dedicated plantations established in Brazil are negligible or moderately negative (see for example, Figures 4.42 and 4.46 in Section 4.10.6). However, as with sources of forest bioenergy from other geographical regions, as considered above, these results depend on underlying assumptions about approaches to forest management and wood use, as described in Section 4.8.3. For newly-established Brazilian biomass plantations, the assumed counterfactual land use is also very influential in determining the estimated impacts on biogenic carbon and consequent GHG emissions.

Based on the preceding assessment, it may be concluded that results estimated for the GHG emissions of forest bioenergy sources, particularly those associated with biogenic carbon of forest biomass, are highly sensitive to the types of forest management involved in increasing levels of forest bioenergy supply.

Furthermore, it may be concluded that the contributions to total annual GHG emissions from sources of forest bioenergy can be significantly reduced if measures are taken to support or encourage approaches to forest management that should ensure more rapid recovery of carbon stocks after harvesting, and the active conservation and enhancement of forest carbon stocks alongside increased harvesting to produce forest bioenergy.

6.7.3. Sensitivities to material wood co-production, utilisation and disposal

As discussed in Sections 6.6, 6.7.1 and 6.7.2, the final project results indicate that the GHG emissions associated with the supply of forest bioenergy are sensitive to a number of factors. The biogenic carbon of forest biomass, litter and soil makes an important (but variable) contribution to GHG emissions, and these are also sensitive to the approaches taken to forest management (see Sections 6.7.1 and 6.7.2). However, there are also potentially important secondary effects due to interactions with the supply of material wood products. The final project results may be analysed further to investigate the sensitivities in such interactions. Such an investigation may also offer some insights into how approaches to the utilisation and disposal of material wood products might be influenced to ensure more positive outcomes in terms of the overall GHG emissions impacts associated with increased forest bioenergy supply.

Figure 6.6a shows total annual GHG emissions for the year 2030, plotted for each scenario, with associated ranges on estimates. The main results have been calculated as explained in Section 6.3, using average emissions factors and referring to the Precautionary' approach to forest management and wood use. The ranges on the main results have been calculated in a similar way but referring to low and high estimates of GHG emissions factors as derived from the pathway workbooks developed in Task 4.

Figure 6.6b shows results equivalent to those in Figure 6.6a, but for the year 2050.

For this project, indirect GHG emissions have been added for biomass energy production and use. This introduces relevant emissions factors, from the pathway workbooks developed in Task 4, which consist of ranges of values. Hence, it is these ranges of emissions factors which are entirely responsible for the ranges in the estimates in Figures 6.6a and 6.6b. In a certain very real sense, this can be viewed as representing genuine uncertainty in results, i.e. it is impossible to be more specific about 'most likely' values for emissions factors from within the ranges that have been defined. It is evident from Figures 6.6a and 6.6b that ranges associated with the estimates of total annual GHG emissions developed for the scenarios in this project are quite large. As already stressed in Section 6.4, consequential LCA studies, by their nature, involve uncertainties such as found in the final project results illustrated in Figures 6.6a and 6.6b. The ranges on estimates early on in the period being studied (e.g. for the year 2010) are much smaller, but sensitivities to emissions factors propagate over time to give the expanding ranges illustrated by the figures for projected estimates for the years 2030 and 2050.

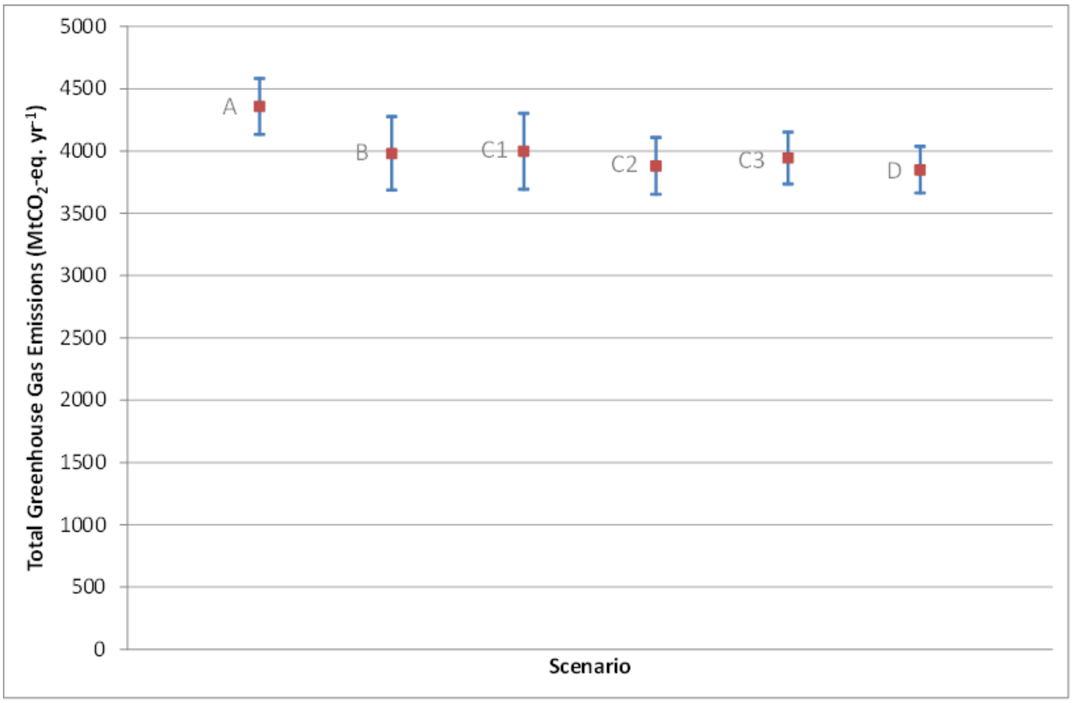

Figure 6.6a. Total annual GHG emissions for all scenarios for the year 2030, showing modelling uncertainties (blue whiskers). Results have been calculated using average emissions factors and referring to the 'Precautionary' approach to forest management and wood use. Ranges have been calculated using low and high estimates for emissions factors.

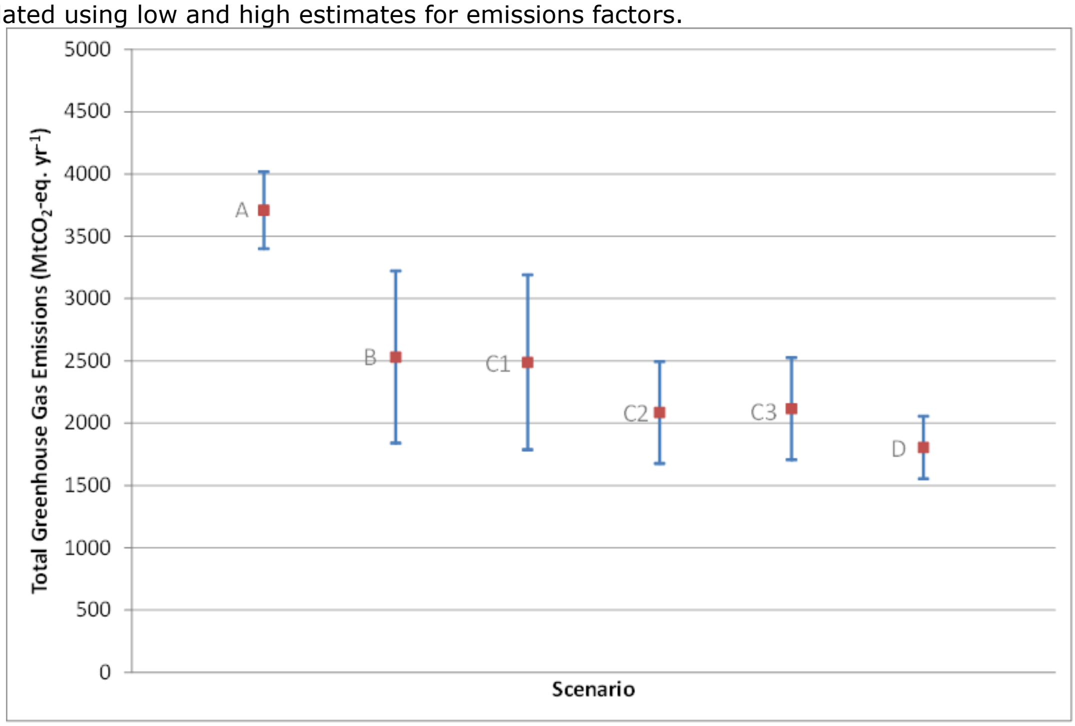

Figure 6.6b. Total annual GHG emissions for all scenarios for the year 2050, showing modelling uncertainties (blue whiskers). Results have been calculated using average emissions factors and referring to the 'Precautionary' approach to forest management and wood use. Ranges have been calculated using low and high estimates for emissions factors.

Despite the presence of significant ranges on the estimates of total annual GHG emissions, for the scenarios developed in this project, as shown in Figure 6.6, the results display some discernible and important features. Importantly, the following conclusions may be drawn.

Even after allowing for significant ranges on estimates, the total annual GHG emissions in 2030 and 2050 are evidently lower for all the various 'Carry on' Scenarios and for the 'Back off' Scenario D, compared with the Reference Scenario A.

Consideration of the ranges on estimates of total annual GHG emissions does not alter the ranking in the results for total annual GHG emissions reductions, as identified for the scenarios developed in this project (see Section 6.5.2). However, the quite large potential ranges on results may be relevant when considering the closeness in outcomes, in terms of GHG emissions reductions, for some of the scenarios.

It should be noted that a major contribution to the ranges on estimates is due to the wide variations in GHG emissions factors for the manufacture and use of material wood co-products (including for their disposal at end of life), and for counterfactual materials. The magnitudes of the GHG emissions that occur when material wood products are disposed of at end of life are very sensitive to the means of disposal. Measures could be taken to encourage the recycling of wood products, and to ensure that their eventual disposal involves approaches that minimise GHG emissions. In principle, measures could also be taken to promote the use of material wood products to displace counterfactuals with high associated GHG emissions. However, it is acknowledged that this may be challenging to achieve in practice.

In Figure 6.7, a further assessment is made of the potential to improve outcomes, in terms of total annual GHG emissions associated with increased forest bioenergy supply, by encouraging approaches to the utilisation of material wood products (co-produced in conjunction with forest bioenergy), that involve positive impacts on GHG emissions. Such approaches involve the processing of material wood products, their specific end uses, their disposal at end of life, and their displacement of counterfactual products.

Figure 6.7 is similar to Figure 6.5, in that it shows the magnitudes of the contributions to overall results in the year 2050 for each scenario, as made by the various categories of GHG emissions sources listed in Section 6.4. Also as in Figure 6.5, two sets of results are shown, referring respectively to the 'Precautionary' and 'Synergistic' approaches to forest management and wood use, each calculated in combination with average GHG emissions factors. However, a third set of results is included in Figure 6.7. These additional results have been calculated by referring to the 'Synergistic' approach to forest management and wood use, in combination with low GHG emissions factors (i.e., 'low', according to the logic explained in Section 6.2). If the results in Figure 6.7 for the 'Synergistic' approach calculated in combination with average GHG emissions factors ('-S') are compared with the results for the 'Synergistic' approach calculated in combination with low GHG emissions factors ('-L'), it is evident that total annual GHG emissions based on low GHG emissions factors are lower, for all scenarios. It is also apparent that the difference in total annual GHG emissions is essentially due to smaller contributions associated with the categories, "CAN Wood Fuel to EU/HWP Co-products" and "USA Wood Fuel to EU/HWP Co-products".

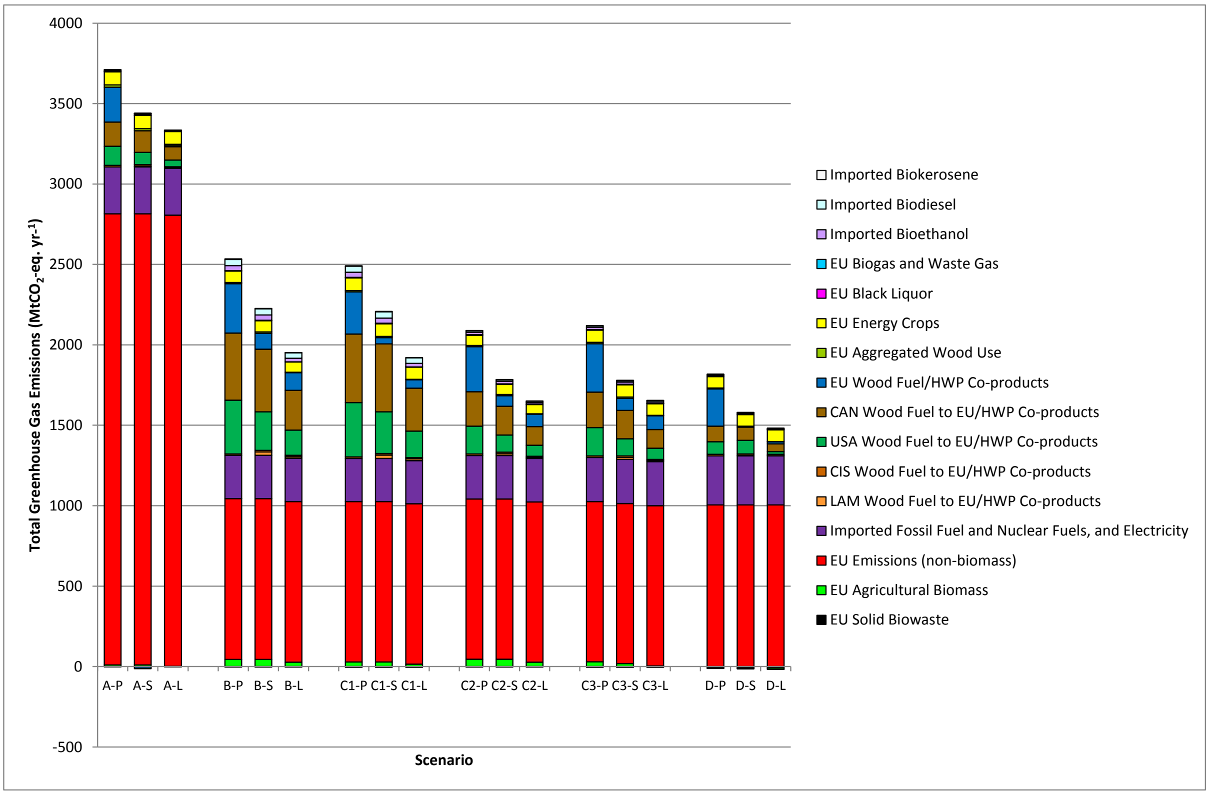

Figure 6.7. Total annual GHG emissions for all scenarios for the year 2050, showing contributions from various sources. Two sets of results have been calculated using average emissions factors and referring to either the Precautionary' approach ('-P') or the 'Synergistic' approach ('-S') to forest management and wood use. A third set of results ('-L') has been calculated using low emissions factors and referring to the 'Synergistic' approach to forest management and wood use.

It is important to recall that, in the discussion of Figure 6.6, it was observed that, in a certain sense, the ranges on estimates of total annual GHG emissions (due to the application of different GHG emissions factors in calculations) represent genuine uncertainty, in that it is impossible to be more specific about 'most likely' values for emissions factors from within the ranges that have been defined. However, based on the assessment of the results in Figure 6.7, it is also the case that these ranges indicate the sensitivity of outcomes, in terms of total annual GHG emissions, to approaches to the utilisation of wood co-produced for material wood products in conjunction with the increased supply of forest bioenergy, in terms of:

- GHG emissions associated with the processing and manufacture of material wood products
- GHG emissions associated with the disposal of material wood products at end of life

- Types of counterfactual products displaced by material wood products, and their associated GHG emissions due to processing, manufacture and disposal at end of life.

Based on the assessments of the results in Figures 6.6 and 6.7, it may be further concluded that the co-production of material wood products in conjunction with the production of forest bioenergy may contribute positively to overall reductions in total annual GHG emissions associated with forest bioenergy supply and consumption, provided that limits for sustainable-yield wood supply are not approached or exceeded (see Sections 4.9.2). However, such a positive contribution is only achieved if:

- *The GHG emissions associated with the processing and manufacture of material wood co-products are [minimised/relatively low]*
- *The displacement of GHG emissions-intensive counterfactual products can be ensured*
- *GHG emissions are minimised when material wood co-products are disposed of at end of life.*

By the same token, the co-production of material wood products in conjunction with the production of forest bioenergy may detract from overall reductions in total annual GHG emissions associated with forest bioenergy supply and consumption, if pathways for the use of material wood co-products involve:

- *Relatively high GHG emissions associated with the processing and manufacture of material wood co-products*
- *The displacement of counterfactual products that are not relatively GHG emissions-intensive*
- *Relatively high GHG emissions when material wood co-products are disposed of at end of life.*

As already acknowledged earlier, in practice, it may be challenging to develop and implement measures that favour positive outcomes for material wood co-products of forest bioenergy, in terms of net impacts on GHG emissions. Further consideration of this issue is beyond the scope of this current project.

6.8. Cost performance of scenarios

Section 6.5 has presented an assessment of the main final project results, expressed in terms of total annual GHG emissions associated with each scenario over the period 2010 to 2050. This assessment has demonstrated that all scenarios that involve further development of existing EU policies on energy, especially bioenergy, are estimated to achieve significant reductions in total annual GHG emissions. These reductions are much greater than those estimated for a Reference Scenario, involving the continuation of existing EU energy policies without further enhancement. The assessment in Section 6.6 has also explored the reasons why several 'decarbonisation' scenarios, representing policies involving increased consumption of bioenergy beyond existing 2020 targets, as well as a scenario representing a 'backing off' from consumption of bioenergy post-2020 all lead to significant reductions in total annual GHG emissions, compared with the Reference Scenario. A key result of this assessment has been that differences in levels of reductions of total annual GHG emissions achieved by the various scenarios involving further development of EU energy policy could be discerned post-2030. In particular, Scenario B, involving the greatest increases in consumption of bioenergy, with limited constraints on bioenergy sources, results in the smallest reductions in total annual GHG emissions out of all the decarbonisation scenarios. Scenario C1, which emphasises the consumption of imported forest bioenergy results in GHG emissions reductions that are close to Scenario B. In contrast, Scenario D, in which the consumption of bioenergy is de-prioritised post 2020, results in the greatest reduction in total annual GHG emissions. Two other scenarios involving increased consumption of bioenergy result in reductions in total annual GHG emissions that are higher, but close to, those estimated for Scenario D. These are Scenario C2, which emphasises the use of agricultural biomass produced in the EU, and Scenario C3, which emphasises the use of forest bioenergy produced in the EU.

If a choice were to be made amongst the scenarios represented in this project, as potential options for future development of EU policy on energy, especially bioenergy, then this would be based in part on consideration of the outcomes of scenarios in terms of the levels of reductions in total annual GHG emissions that would be achieved. However, this is unlikely to be the only consideration, particularly given the closeness of outcomes for several scenarios.

An assessment of options involving the future consumption of biomass for energy in the EU, based on a wider set of criteria than "carbon impacts", is a topic that is worthy of further study and research. As such, this is highlighted as part of the conclusions from this project in Section 7.3, whilst noting the very large uncertainties likely to be associated with the assessment of some criteria (e.g. impacts on biodiversity). Strictly, further consideration of other criteria for assessing scenarios is beyond the scope of this current project. However, the information available to this project from the results of underlying PRIMES scenarios, combined with the results directly developed in this project, does permit an assessment to be made of the cost performance of the various scenarios, expressed in terms of Euros per tonne of GHG emissions abated (i.e. in units of €/tCO_2-eq.), and as a share of GDP (i.e. in % of GDP). Such assessments are presented in the ensuing discussion.

6.8.1. Estimation of cost performance of scenarios

For simplicity and clarity, the estimation of cost performance has referred to the results for total annual GHG emissions over time, as estimated for the various scenarios developed in this project, based on the application of average emissions factors in calculations and the 'Precautionary' approach to forest management and wood use.

The method for estimating the cost performance of the scenarios has involved calculating the marginal GHG emissions reductions, and the marginal cost of each scenario, by comparing the results for each scenario with the results for the Reference Scenario A. The developments involved in moving from the situation described in the Reference Scenario A to achieve the outcomes represented by the decarbonisation scenarios (B, C1, C2, C3 and D), would require extensive investments towards more efficient technology and infrastructure. Additionally, the decarbonisation scenarios require other measures aimed at deep GHG emissions reductions. Some of these measures are discussed in the detailed analysis of the final project results in Sections 6.9.1 to 6.9.3. The VTT-TIAM model, which was used in the development of the project scenarios in Task 2, minimises the costs to produce the most cost-efficient solutions for each scenario, within the set constraints and assumed resources. Costs are presented as a share of projected GDP, and as an average GHG reduction cost, where the cumulative total annual GHG reductions of each scenario are divided by the cumulative costs.

The VTT-TIAM model also calculates the marginal carbon price, which reflects the price of the most expensive greenhouse gas abatement measure each year. Up to 2020, this price indicates the price of the emissions allowance unit referred to in the EU ETS and, from 2020 to 2050, the reported price covers all GHG emission inventory sectors and thus cannot be directly interpreted as the carbon price of the EU ETS. By 2050, all sectors have to reduce their emissions, and the carbon price increases to a relatively high level in each scenario to achieve these deep reductions.

The marginal reduction cost gives more information about the performance of the scenarios when combined with average reduction costs. If the marginal abatement curve is flat at the beginning but really steep at the end, the marginal cost might be high, but the average cost may remain at relatively low level. If the average reduction cost is also high, this implies that implementation of the scenario would require multiple measures that will be expensive and most likely difficult to realise.

It is important to stress that the estimation of costs associated with the scenarios developed in this project inevitably involves considerable uncertainties, as for any such economic modelling exercise. Section 3.6 has discussed some these issues, particularly with regard to limited and uncertain data on the costs associated with future supplies of biomass, and has described a number of the assumptions made about these costs. The discussion in Section 3.6 also describes the efforts made in Task 2 to ensure that the cost estimates referred to in the modelling of bioenergy chains were not underestimated.

It should be noted that, as explained in Section 3.4.1, the VTT-TIAM model is able to assess and allow for costs of actions in the energy system (i.e. somewhat wider than just the energy sector), but does not represent all potential costs in other sectors. A notable source of uncertainty in the cost estimates involved in the calculation of results considered below is related to shifts in the use of wood produced for material wood products and concomitant changes in the consumption of counterfactuals. However, cost estimates for different scenarios are calculated on a common and consistent basis and, as such, are comparable with one another.

As already stated, the cost performance estimates considered here are based on the results for GHG emissions reductions based on the ‘Precautionary’ approach to forest management and wood use. The estimation of equivalent results based on the ‘Synergistic’ approach would not be advisable, because the costs of the additional measures aimed at conserving and enhancing forest carbon stocks alongside increased bioenergy consumption have not been estimated.

As with the results of any economic modelling exercise, the results presented below should be interpreted with appropriate caution. In this respect, the assessment of the relative performance of the scenarios, as judged by comparison of cost performance estimates (e.g. if used to rank the scenarios), may be more robust, whereas the absolute values of estimates for cost performance measures may be less certain.

6.8.2. Results for cost performance of scenarios

Table 6.5 shows the estimated additional energy system costs of each scenario compared with the GDP projection of the EU. The total additional energy system-related costs (% of GDP) are very similar for various 'Carry on' Scenarios. From this specific perspective, all 'Carry on' Scenarios perform about equally well. Scenario D ('Back off') stands out as considerably more expensive than the 'Carry on' Scenarios, particularly in 2050.(In 2030, the estimated carbon price for Scenario D is between 10% and 40% greater than the equivalent results for the 'Carry on' Scenarios; in 2050 it is between 1.6 and 2.2 times greater.)

The marginal cost levels (carbon prices) of the 'Carry on' Scenarios are all at a roughly similar level in 2030, although the result for Scenario C3 ('Carry on/domestic wood') is somewhat lower, whilst the result for Scenario B ('Carry on/unconstrained use) is somewhat higher. These differences between the marginal carbon prices for the 'Carry on' Scenarios are more pronounced in the results for 2050. Additionally, the, the marginal carbon price in 2050 for Scenario C1 ('Carry on/imported wood') is marginally lower than for Scenario C2 ('Carry on/domestic crops'). Based on this indicator, Scenario D ('Back off') performs considerably worse than the 'Carry on' Scenarios. (In 2030, the estimated additional energy system cost for Scenario D is more than 3 times greater than the equivalent costs for the 'Carry on' Scenarios; in 2050 it is around 1.8 times greater.)

The last column of Table 6.5 shows the average reduction cost, which compares the cumulative energy system costs to the cumulative total annual GHG emissions reductions between 2010 and 2050. This gives a third indication of performance with regard to the costs of the scenarios. Scenarios B ('Carry on/unconstrained use') and C1 ('Carry on/import wood') achieve smaller reductions in GHG emissions compared with the other 'Carry on' Scenarios, and the average reduction cost for Scenarios B and C1 is higher. Additionally, whilst the carbon price associated with Scenario C2 ('Carry on/domestic crops') is higher than for the other 'Carry on' Scenarios, it has the smallest average GHG reduction cost out of all these scenarios. Though Scenario D achieves bigger reductions in GHG emissions than the 'Carry on' Scenarios, it is a considerably more expensive scenario according to this indicator. (The average GHG reduction cost for Scenario D is between 1.5 times and 1.9 times the equivalent costs for the 'Carry on' Scenarios.)

Table 6.5 Results for cost performance of the 'Carry on' Scenarios and 'Back off' Scenario

Scenario	Marginal energy system cost (% of GDP) for year		Marginal carbon price (€/tCO_2) for year		Average GHG reduction cost 2010-2050 (€/tCO_2)
	2030	2050	2030	2050	
B ('Carry on/ unconstrained use')	0.18%	0.90%	48	196	122
C1 ('Carry on/ imported wood')	0.19%	0.89%	43	147	125
C2 ('Carry on/ domestic crops')	0.18%	0.91%	43	160	96
C3 ('Carry on/ domestic wood')	0.20%	0.91%	38	138	100
D ('Back off')	0.63%	1.59%	53	310	183

Based on the above assessment of the cost performance of the 'Carry on' Scenarios and the 'Back off' Scenario D, the following conclusions may be drawn.

The 'Back off' Scenario D stands out as significantly more expensive, in terms of cost performance, compared with all of the 'Carry on' Scenarios:

- *By between around 315% (compared with Scenario C3) and 350% (compared with Scenarios B and C2) in 2030, falling to between around 175% (compared with Scenarios C2 and C3) and 180% (compared with Scenario C1) in 2050,* ***based on the marginal energy system cost*** *(note that the projected GDP in 2030 and 2050 is the same in all scenarios)*
- *By between around 110% (compared with Scenario B) and 140% (compared with Scenario C3) in 2030, rising to between around 160% (compared with Scenario B) and 225% (compared with Scenario C3) in 2050,* ***based on the marginal carbon price***
- *By between around 145% (compared with Scenario C1) and 190% (compared with Scenario C2),* ***based on the average GHG reduction cost over the period 2010 to 2050.***

Differences between the cost performance of the various 'Carry on' Scenarios are smaller. However, Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood') appear to give the most favourable results in terms of overall cost performance and levels of reductions in total annual GHG emissions.

It should be stressed that the poorer cost performance of Scenario D, in comparison with the 'Carry on' Scenarios, does not imply that the other renewable energy sources used in place of bioenergy in Scenario D must cost significantly more than bioenergy sources. Rather, the higher costs of Scenario D are associated generally with challenges involved in meeting the targets set for levels of renewable energy consumption and GHG emissions reductions, whilst also de-prioritising the consumption of bioenergy. In this respect, the results for Scenario D indicate that the available lower-cost options are not sufficient to meet the targets set for renewable energy supply and GHG emissions reductions, if bioenergy is not also available as an option, therefore higher-cost options also need to be included as part of actions taken.

The modelling of the high-bioenergy 'Carry on' Scenarios in this project has involved identifying a cost-optimal mix of energy sources and conversion technologies for energy supply in the EU region. This involves selecting all the cheapest sources of energy and conversion technologies needed to meet the final energy demand. In the 'Carry on' Scenarios, most of the biomass specified as available for consumption is selected because of its relatively low cost, along with other low-cost sources of renewable energy, for example, low-cost wind power generation. When the use of bioenergy is constrained (such as in Scenario D), the remaining available lower-cost energy options are not sufficient to meet the targets set for renewable energy supply and GHG emissions reductions, hence, higher-cost options also need to be included as part of actions taken (for example, wind power installations in low-wind areas, with higher associated costs).

When assessing and comparing the scenarios developed in this project, the measures of cost performance discussed in this section can be regarded as a complement to the results for the reductions in total annual GHG emissions achieved by the scenarios, as described in Section 6.5. However, as stressed repeatedly in earlier discussions, it is important to note that further, detailed analysis is required to fully understand the contribution made specifically by bioenergy, as already discussed in Sections 6.6 and 6.7, and further discussed in Section 6.9.

6.9. Detailed analysis of final project results

Thus far, the discussion of the final project results has focused mainly on the estimated changes in the total annual GHG emissions associated with each of the scenarios developed in this project, with some limited consideration of specific sources of GHG emissions contributing to overall changes. Such an approach is consistent with the conventions of consequential LCA, and with the LCA goal stated in the project purpose at the outset, in Section 1.2.2 (see also related discussion in Section 6.4). This assessment of the final project results has revealed a number of insights and enabled some important conclusions to be drawn. In particular, several scenarios, involving more ambitious targets for consumption of renewable energy sources and GHG emissions reductions, have been identified as achieving significant additional reductions in GHG emissions over the period 2020 to 2050, compared with a Reference scenario, in which there are no additional targets set after 2020. Amongst these, a scenario involving the de-prioritisation of the consumption of bioenergy after 2020 (Scenario D, 'Back off') achieves the biggest reductions in total annual GHG emissions, although at relatively high cost. Two scenarios involving the increased consumption of bioenergy (Scenario C2, 'Carry on/domestic crops' and Scenario C3, 'Carry on/domestic wood') achieve reductions in total annual GHG emissions that are quite close to those of Scenario D. This has led to the observation (Section 6.5.1) that, in the context of future development of EU energy policy, the 'bioenergy option' may be viewed as neither a 'show-stopper' nor a 'must-have' from the simple perspective of GHG emissions alone. However, the discussion so far has also repeatedly stressed that further, detailed analysis is required to fully understand the contribution made specifically by bioenergy, as already discussed in Sections 6.6 and 6.7. There remain a number of key issues concerning the contribution made by bioenergy which require further investigation:

- The significance of the contributions made specifically by bioenergy sources towards total primary energy supply, under the various scenarios considered in this project
- The actual magnitudes of the contributions made by bioenergy sources towards achieving net reductions in GHG emissions, under the various scenarios considered under this project (beyond the assessments already presented in Sections 6.6 and 6.7)
- Whether specific forest bioenergy sources can be distinguished as better or poorer for achieving net reductions in GHG emissions (beyond the assessments already presented in Sections 6.6 and 6.7)
- The relevance (or otherwise) of the contribution of bioenergy sources towards the EU's climate and energy goals for 2030
- Whether levels or criteria need to be set for the future consumption of bioenergy sources, to ensure its effective contribution towards the EU's climate and energy goals for 2030.

These issues have been explored by carrying out a more detailed analysis of the final project results, as described below. Some further elaboration of these points, based on this analysis, is discussed in Section 6.10.

6.9.1. Approach to detailed analysis

In order to understand the approach taken to the detailed analysis of the final project results, first of all it is important to understand how biomass and bioenergy were defined for the purposes of detailed analysis. In the context of energy supply, biomass is a collective term which describes all organic materials from which suitable forms of energy including fuels, heating, cooling and electricity, often referred to as bioenergy, can be derived.

It is also important to recall certain aspects of the approach taken to the modelling of the scenarios developed in this project, as described in Sections 3 to 5, and how this was developed in the detailed analysis.

The assessment of the carbon impacts of bioenergy consumed in the European Union (EU) was undertaken by estimating the total GHG emissions associated with:

- The combustion of fossil fuels and releases from prominent industrial and agricultural activities within the EU
- The provision of fossil and nuclear fuels, and electricity imports into the EU

- Specifically, the changes in carbon sequestration and biogenic carbon emissions in forests and agricultural systems, and the indirect GHG emissions of bioenergy supply within and outside the EU.

The assessment was performed by simulating primary energy supply in the EU27 region between 2010 and 2050 with the VTT-TIAM model, for each of the scenarios defined in this study. To achieve this, for each scenario, the VTT-TIAM model was used to simulate changes in the consumption, not only of bioenergy sources, but also other relevant energy sources, including other renewable energy sources, nuclear energy and fossil energy sources. In addition, VTT-TIAM simulated changes in the technologies deployed as part of energy conversion, as well as measures aimed at achieving energy efficiency. Absolute total GHG emissions associated with all these changes in the use of energy were also simulated by the VTT-TIAM model, along with certain measures aimed at mitigation of GHG emissions, notably carbon capture and storage (CCS). The estimates for GHG emissions produced as outputs by the VTT-TIAM model were supplemented by additional modelling for bioenergy sources, and for certain other energy sources not fully represented in the VTT-TIAM model. For bioenergy sources, the modelling allowed for changes in carbon sequestration and biogenic carbon emissions in forests, as well as indirect GHG emissions associated with biomass supply and any land use changes. For this purpose, it was necessary to model the development of forest carbon balances with and without the additional forest bioenergy production represented in each scenario. The latter instance without forest bioenergy production constituted a counterfactual scenario for land use, for comparison with the situation in which forest bioenergy production takes place in forests. This counterfactual scenario consisted of business-as-usual forest management and wood use, in the EU and other relevant countries. Effectively, net changes in forest carbon sequestration and biogenic carbon emissions, are built in to the total GHG emissions estimates for all the scenarios under consideration.

The modelling approach adopted in this project has some important consequences for the results and their interpretation, crucially:

- The projected future supply of total primary energy involves changes in the use of many different sources of energy, not just bioenergy or more specifically forest bioenergy, and also changes in conversion technologies deployed and measures aimed at achieving greater energy efficiency. This can make the contribution to total primary energy supply made solely by bioenergy difficult to discern.
- The projected results for total annual GHG emissions are due to the combination of changes in the use of various energy sources, with associated changes in efficiencies and mitigation measures, which can make the impacts specifically due to bioenergy difficult to distinguish.

This complex approach to the modelling of scenarios in this project was necessary in order to assess, quantitatively, the potential role of bioenergy sources in contributing to future energy supply in the EU. Hence, it was a requirement of the project that the scenarios for future bioenergy consumption in the EU were developed in relation to existing scenarios for total primary energy use, namely, the PRIMES scenarios, produced for the European Commission in 2013 (see Appendix 2). These scenarios were pertinent because they were referred to in the impact assessment of the communication on the policy framework for climate and energy in the period from 2020 up to 2030. As explained in Section 3 of this report, the PRIMES reference scenario was referred to in the development of the Reference Scenario A for bioenergy consumption, as represented in this project. The EEMRES30 decarbonisation scenario was referred to in developing the various decarbonisation scenarios in this project, representing either increased or decreased emphasis on bioenergy consumption after 2020.

Since scenario A follows the PRIMES 2013 reference scenario, without additional targets for GHG emissions and renewable energy supply after 2020, its results provide a basis against which those of all the other scenarios can be compared. Such a basis for comparison was important in the following detailed analysis, because it enabled the assessment of changes in the contributions made by various energy sources, including bioenergy sources, to total primary energy supply, associated with the decarbonisation scenarios. It was also possible to determine future relative reductions in total GHG emissions associated with the decarbonisation scenarios. This was achieved by subtracting the results for consumption of energy sources and total GHG emissions (as estimated by the VTT-TIAM model), for the Reference Scenario A, from those for each of the decarbonisation scenarios.

It should be noted that the projected changes in energy use under each scenario, as simulated by the VTT-TIAM model, did not follow exactly the projected pattern of changes represented in the underlying PRIMES scenarios. However, the modelling methods underlying the PRIMES scenarios are very similar to those adopted in the VTT-TIAM model. Furthermore, information from the PRIMES scenarios was used in the calibration of the VTT-TIAM model, as part of the development of the scenarios in this project, with the result that, in general, the outputs of VTT-TIAM were compatible with the PRIMES scenarios on which they were based.

6.9.2. Contribution of bioenergy to total energy supply and consumption

The projected contributions made by bioenergy, and by renewable energy sources in general, to energy use in the EU region have already been discussed in Sections 3.7.1 to 3.7.3. The following discussion considers the contributions made by bioenergy to overall energy use in the EU27 region, with regard to both TPES and final energy consumption. The outputs of the VTT-TIAM model provide annual estimates for both these measures of energy use. It is important to understand the definitions of TPES and final energy consumption, and the distinction between these two measures, as given below.

TPES represents the energy produced and used within a specified region, excluding exported energy, but including energy imported into the specified region, prior to any transportation and conversion within the region as part of final consumption. This means that, for the example of the EU27 region, TPES represents:

- Energy produced and used within the EU27 region, i.e. excluding any energy produced within the EU27 region and exported to elsewhere
- Energy imported into the EU27 region from elsewhere.

Final energy consumption represents all energy supplied *to final consumers* within a specified region for all energy uses, i.e. allowing for losses from transportation, conversion and other inefficiencies related to use of the energy within the specified region.

TPES, as projected over the period 2010 to 2050, is similar for all scenarios, and is typically around 1 560 Mtoe.

The VTT-TIAM model disaggregates the bioenergy contribution to TPES into the following 4 broad categories:

- Biomass; predominantly composed of biomass obtained from agriculture, forests and other primary sources
- Bioliquids; mainly consisting of biofuels that can be used to displace liquid fuels derived from fossil fuels
- Biogas; biomethane and synthetic natural gas produced by a number of different processes from a variety of different types of biomass
- Biowaste; chiefly domestic, commercial and industrial solid wastes.

In 2030, the contribution of bioenergy to TPES in Scenario A ('Reference') is relatively low, at 11.0%, and even lower in Scenario D ('Back off'), at 8.5%. The contributions of bioenergy to TPES are higher and quite similar for the other scenarios. In particular, the contribution made by bioenergy is highest in Scenario B ('Carry on/unconstrained use'), at 15.1%, and lowest in Scenario C1 ('Carry on/imported wood'), at 14.1%.

In 2050, the contribution of bioenergy to TPES in Scenario A ('Reference') remains relatively low, at 10.8%, and even lower in Scenario D ('Back off'), at 9.2%. The contributions of bioenergy to TPES in the other scenarios are higher than in 2030 and quite similar to each other. In particular, the contribution made by bioenergy is highest in Scenario B ('Carry on/unconstrained use'), at 22.7%, and lowest in Scenario C3 ('Carry on/domestic wood'), at 18.3%. Scenarios C1 ('Carry on/imported wood') and C2 ('Carry on/domestic crops') have very similar bioenergy contributions of 19.4% and 19.6%, respectively. However, these projected estimates for contributions made by bioenergy to TPES in 2050 should be regarded with caution. An assessment in Section 4.10.4 suggested that the levels of forest bioenergy production represented in the scenarios by 2050 are likely to involve very significant risks to the sustainable-yield supply of wood from within the EU27 region, and also risks for at least some importing regions. Furthermore, a provisional assessment in Section 4.10.6 of biogenic carbon emissions associated with forest bioenergy supply suggested that such emissions could be significant, particularly if the level of supply rose continually, as represented in the high-bioenergy scenarios, and notably due to a pronounced increase in supply to meet the levels projected for 2050. This point is returned to in Section 6.9.4.

The contributions of bioenergy, and renewable energy sources in general, to energy use in the EU region can also be expressed in terms of final energy consumption (as opposed to TPES). This has also been discussed in Section 3.7.1.

For the Reference Scenario A, the contribution of bioenergy to final energy consumption in 2030 is about 12%. The contribution is similar for Scenario D ('Back off'). For the high-bioenergy scenarios, the contribution of bioenergy to final energy consumption in 2030 is higher, at around 17% to 18%.

In terms of the contribution of all renewable energy sources to final energy consumption in 2030, all the decarbonisation scenarios reach a target in 2030 for renewable energy consumption of 30% (as represented in the PRIMES EEMRES30 scenario, and set as a parameter in the VTT-TIAM model for these scenarios). In the Reference Scenario A, the share due to renewable energy remains at 25%. After 2030, the renewable energy share increases further in the decarbonisation scenarios, to about 45% by 2050.

These results, particularly the results for 2030, suggest some significant conclusions for EU policy, since the Climate and Energy Policy Framework specifies that "an EU target of at least 27% is set for the share of renewable energy consumed in the EU in 2030" (European Council, 2014).

Specifically, the preceding assessment suggests that the 2030 target for contributions to "energy consumed in the EU" (assuming this refers to final energy consumption), from renewable energy sources would be met under all scenarios considered in this project, with the exception of the Reference Scenario A. It may be noted that the high-bioenergy scenarios typically involve contributions from bioenergy to final energy consumption of about 17% to 18%, and to TPES of about 14% to 15%.

With regard to the above conclusion, it is important to recall that, as highlighted in Section 6.9.1, the modelling of the scenarios developed in this project simulated the potential development of a range of possible renewable energy sources, not just bioenergy, and also represented measures aimed at improved energy conversion and efficiency. (See later discussion of Figure 6.9 and Table 6.6.)

A detailed breakdown of contributions to TPES in the EU in 2030 is presented in Figure 6.8. It can be seen that the contribution of biomass to TPES in Scenario A ('Reference') is relatively low, at 8.0%, and even lower in Scenario D ('Back off'), at 5.7%. The biomass contributions to TPES are higher and quite similar for the other scenarios at around 11% to 12%. In particular, the biomass contribution is highest with Scenario B ('Carry on/unconstrained use'), at 12.1%, and lowest with Scenario C1 ('Carry on/imported wood'), at 10.9%. Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood') have biomass contributions of 11.8% and 11.2%, respectively. A possible conclusion may be drawn from these results.

Specifically, if biomass were to be used to contribute towards the EU's 2030 target for consumption of renewable energy sources, then the contribution of biomass to TPES *would need to be around 11% to 12%. Noting that, in the VTT-TIAM model, biomass includes contributions to TPES made by black liquor (a by-product of paper manufacture, see Section 3.7.2), then, based on results reported above and in Section 3.7.2, the contribution of primary sources of agricultural and forest biomass (i.e. not including black liquor) to TPES would need to be around 10% to 11%.*

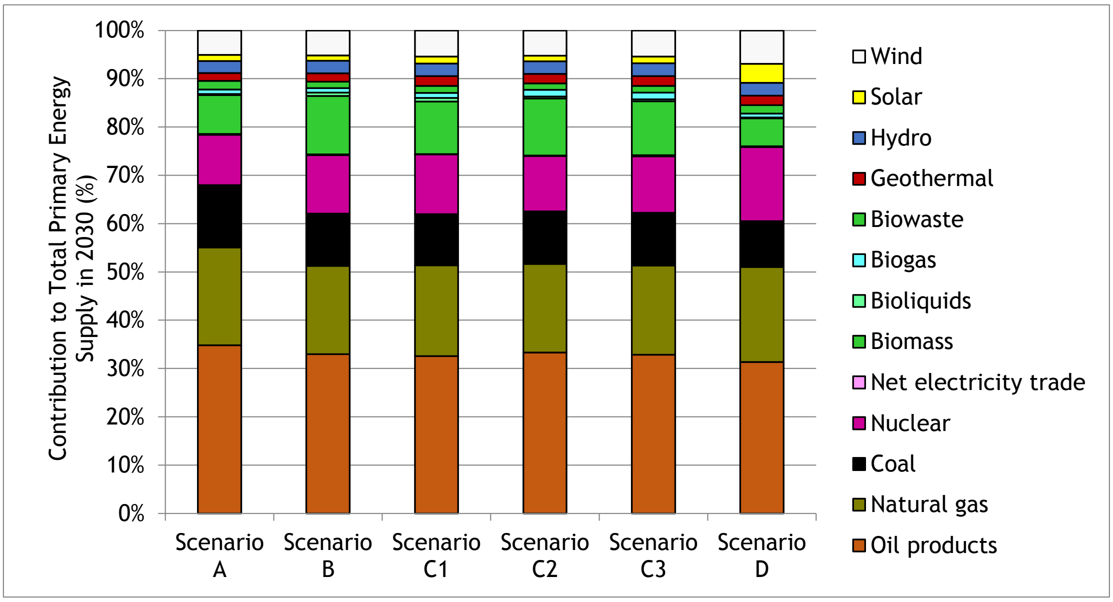

Figure 6.8. Detailed contributions to Total Primary Energy Supply in the European Union in 2030.

In general terms, there are similar contributions to TPES from biomass under the high-bioenergy scenarios. However, there are markedly different contributions to TPES due to biomass apparent for Scenario D (‘Back off’). In particular, the reduction in the contribution of biomass to TPES, compared with the high-bioenergy scenarios, is compensated for by greater dependence on wind, solar and, especially, nuclear power.

As explained in the description of the approach to the detailed analysis in Section 6.9.1, the changes in energy use projected under the different scenarios can be demonstrated more prominently by considering the contributions to TPES under the decarbonisation scenarios, relative to those for the Reference Scenario A. Such an analysis, based on the results for the year 2030, is illustrated in Figure 6.9. For all the decarbonisation scenarios, there are very significant relative decreases in the contribution to TPES due to oil products from fossil fuels. These relative reductions are counteracted by significant relative increases in the TPES contribution from biomass supply in the high-bioenergy scenarios. However, a relative fall in the TPES contribution from biomass in Scenario D (‘Back off’) is counteracted by a large relative increase in nuclear power, as well as relative increases in solar and wind power, and smaller reductions in natural gas.

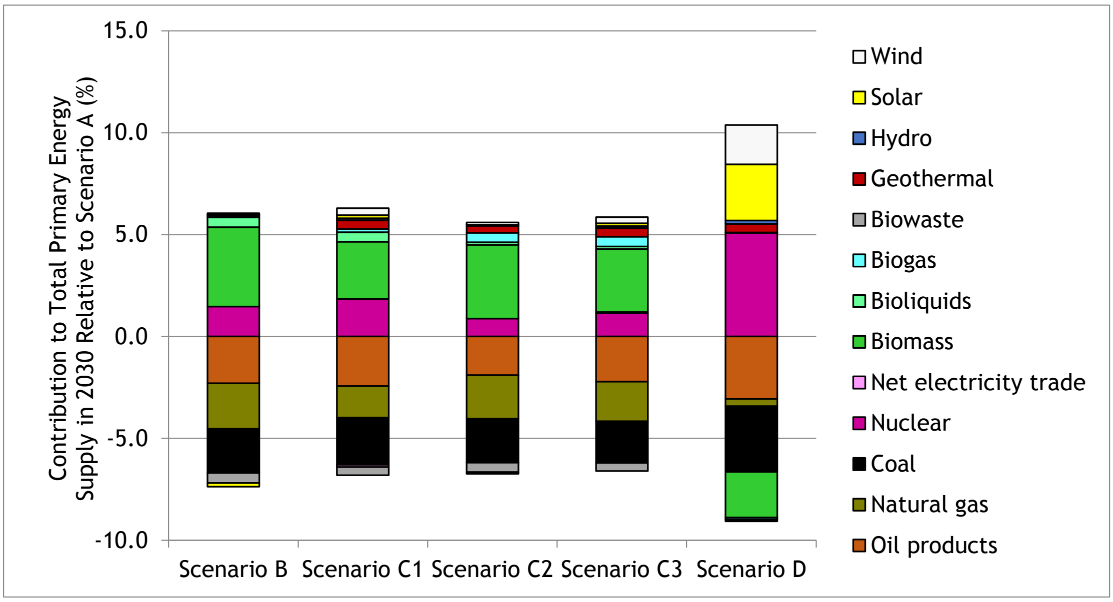

Figure 6.9. Detailed contributions to Total Primary Energy Supply in the European Union in 2030, for the decarbonisation scenarios, relative to Reference Scenario A.

Further details of the main changes in contributions to TPES in the EU in 2030 and 2050 are summarised in Table 6.6. In addition to relative changes in contributions from different sources of energy supply, it can be seen that there are also differences in the overall magnitude of TPES under the decarbonisation scenarios, relative to the Reference Scenario A. This is interpreted as indicating the effects of relative changes due to measures aimed at improved energy efficiency.

Table 6.6 Main changes in contributions to Total Primary Energy Supply in European Union in 2030 and 2050, relative to Reference Scenario A

Scenario	Main Changes Relative to Scenario A	
	2030	2050
B	Oil products, coal and natural gas decrease (6.6%), biomass increases (3.9%), and total primary energy supply decreases (1.3%).	Oil products decrease (16.2%), biomass increases (10.2%), wind increases (3.0%), and total primary energy supply decreases (1.2%).
C1	Oil products, coal and natural gas decrease (6.2%), biomass increases (2.8%), and total primary energy supply decreases (0.5%).	Oil products decrease (16.2%), biomass increases (6.8%), wind increases (3.9%), and total primary energy supply decreases (1.4%).

Table 6.6 (continued) Main changes in contributions to Total Primary Energy Supply in European Union in 2030 and 2050, relative to Reference Scenario A

Scenario	Main Changes Relative to Scenario A	
	2030	2050
C2	Oil products, coal and natural gas decrease (6.1%), biomass increases (3.6%), and total primary energy supply decreases (1.1%).	Oil products decrease (15.8%), biomass increases (7.6%), wind increases (2.8%), and total primary energy supply decreases (1.5%).
C3	Oil products, coal and natural gas decrease (6.1%), biomass increases (3.1%), and total primary energy supply decreases (0.7%).	Oil products decrease (16.0%), biomass increases (6.4%), wind increases (2.9%), and total primary energy supply decreases (1.2%).
D	Oil products, coal and natural gas decrease (6.7%), biomass decreases (2.2%), wind increases (1.9%), solar increases (2.8%), and total primary energy supply increases (1.3%).	Oil products decrease (14.8%), nuclear increases (6.7%), biomass decreases (1.7%), wind increases (3.3%), solar increases (1.6%) and total primary energy supply decreases (1.1%).

Overall, prominent changes relative to scenario A in 2050 can be summarised as follows:

- All scenarios have substantial decreases in oil product supply relative to Reference Scenario A
- Biomass energy supply relative to Reference Scenario A has the largest increase in Scenario B, smaller but similar increases in Scenarios C1, C2 and C3, and a substantial decrease in Scenario D (earlier cautionary remarks about the levels of forest bioenergy supply projected for 2050 need to be borne in mind)
- Wind power increases relative to Reference Scenario A for all the scenarios
- Increases in solar power relative to Reference Scenario A are apparent for Scenario D
- Total primary energy supply relative to Reference Scenario A has the largest decrease in Scenario C2, followed closely by the decreases in Scenario C1, then by similar decreases in Scenarios B and C3, and finally by the decrease in Scenario D
- Nuclear power increases substantially in Scenario D relative to Reference Scenario A.

6.9.3. Contribution of bioenergy to GHG emissions reductions

A much more involved procedure was required to determine the contribution of biomass to reductions in total GHG emissions, relative to Reference Scenario A. This is because of the nature of the VTT-TIAM model and its use in this assessment. In particular, reductions in total GHG emissions due to individual contributions to TPES are not directly reported as part of the outputs of the VTT-TIAM model. However, it is possible to approximate contributions to total GHG emissions reductions by combining results from the VTT-TIAM model and from the final results workbook, "EC BCI Results v40.xlsx", and by applying certain simplifying assumptions. Before describing the details of this procedure, it is necessary to establish the main means of GHG emissions mitigation. The most apparent means in the VTT-TIAM model which will displace GHG emissions from fossil fuels directly are:

- Bioenergy, consisting of biomass, bioliquids, biogas and biowastes
- Other renewable energy sources, consisting of wind, solar, hydro and geothermal
- Nuclear power.

However, as explained in Section 6.9.1, there are also other important means of GHG emissions mitigation which are energy efficiency and CCS. The relative role of energy efficiency can be approximated by using differences in overall TPES for each scenario, based on the results from the VTT-TIAM model. In particular, it is assumed that some indication of the relative impact of energy efficiency can be determined by subtracting the overall TPES of the decarbonisation scenarios from the overall TPES of scenario A. It must be appreciated that this is a necessary but very approximate means of estimating the contribution of energy efficiency. This is because this approach is, in effect, based on a highly simplifying assumption of exact equivalence of different energy sources. In other words, one unit of energy from any one source can exactly replace one unit of energy from any other source. Whilst such exact equivalence is unlikely in all cases, it is a convenient first approximation which is acceptable within the constraints and use of subsequent results.

The relative effects of CCS can only be estimated using assumptions about its application. The contributions of CCS to relative GHG emissions reductions become increasingly important from 2030 onwards in all scenarios according to the VTT-TIAM model. This is illustrated in Table 6.7, which summarises the estimated share of electricity generation from power-only plants and from district heat and power (DHP) plants with CCS in the EU27 region, under each scenario. Examination of the relevant detailed outputs from the VTT-TIAM model indicated that CCS was assumed to be applied to coal-fired and natural gas-fired power-only plants, and to coal-fired, natural gas-fired and biomass-fired DHP plants in all scenarios from 2030 onwards. However, the VTT-TIAM model does not directly represent biogenic carbon emissions from biomass (these were modelled separately in this project in Task 3). Because of this, the VTT-TIAM model typically greatly underestimates the potential for GHG emissions reductions associated with biomass-fired DHP plants through application of CCS.

Table 6.7 Application of carbon capture and storage to electricity and combined heat and power generation in the European Union

Scenario	Share of Electricity from Power Only and District Heat and Power Plants with Carbon Capture and Storage (%)				
	2030	2035	2040	2045	2050
A	0.4	1.1	1.8	4.4	5.9
B	0.8	6.3	12.4	22.7	24.8
C1	0.8	4.8	12.7	21.9	27.2
C2	0.8	6.2	12.4	17.3	22.9
C3	0.8	5.4	12.2	18.3	25.6
D	1.0	5.6	13.8	20.4	26.5

The contributions of CCS to reductions in GHG emissions for each scenario were estimated by assuming that 70% of the carbon dioxide would be captured and stored, and that the direct GHG emissions factors for coal and natural gas combustion are 0.0953 $kgCO_2$-eq. MJ^{-1} and 0.0562 $kgCO_2$-eq. MJ^{-1}, respectively. Given the effective non-application (or more strictly minor application) of CCS to wood-fired DHP plants, avoided GHG emissions from wood combustion were not taken into account. The assumed net thermal efficiencies of electricity generation by fossil-fired power-only and DHP plants are summarised in Table 6.8. Approximate annual avoided GHG emissions were calculated for each scenario by combining the above assumptions with estimates of annual electricity generation from plants with CCS.

Table 6.8 Assumed Net Thermal Efficiencies of Electricity Generation by Fossil-fired Power Only and District Heat and Power Plants

Plant Type	Net Thermal Efficiency of Electricity Generation (%)
Coal-fired Power Only	35
Natural Gas-fired Power Only	45
Coal-fired District Heat and Power	25
Natural Gas-fired District Heat and Power	30

The next step in the procedure was to determine the annual GHG emissions avoided by CCS in the decarbonisation scenarios, relative to those in Reference Scenario A, by means of subtraction. The difference between estimated annual total GHG emissions for the decarbonisation scenarios and those for Reference Scenario A, obtained using the VTT-TIAM model, were then derived also by subtraction. Subsequently, the relative annual GHG emissions avoided by CCS were subtracted from the relative annual total GHG emissions to obtain the relative annual GHG emissions avoided by all other means of mitigation. By this approach, the contributions of CCS to estimates of reductions in GHG emissions could be differentiated from other contributions.

It was then necessary to establish the contributions of the various other means of mitigation to the results for relative annual GHG emissions reductions. Without further detailed information, another simplifying assumption was applied. This was that such contributions should be divided between these means of mitigation on the basis of their proportional contributions to the differences in TPES under the decarbonisation scenarios, relative to Reference Scenario A. This approach was applied to relative total annual GHG emissions adjusted appropriately for net differences in carbon sequestration and biogenic carbon emissions, and differences in indirect GHG emissions associated with bioenergy. Subsequently, such adjustments were subtracted from the contributions to differences in GHG emissions reductions due to the specific use of bioenergy relative to Reference Scenario A. The resulting relative contributions to GHG emissions reductions are subsequently referred to as “bioenergy (net)”.

It should be noted that, due to simplifying assumptions, the results of this analysis should only be regarded as indicative rather than completely precise. This approach is adequate for identifying major contributions to net GHG emissions savings in each decarbonisation scenario. However, on the basis of known approximations, no particular significance should be attached to any minor contributions.

Since differences in carbon sequestration and biogenic carbon emissions, and in indirect GHG emissions associated with bioenergy depend on the specified type of forest management, separate results were generated for the 'Precautionary' (P) and 'Synergistic' (S) approaches to forest management and wood use (see Section 4.8.3). Finally, the absolute contributions (expressed in units of $MtCO_2$-eq. yr^{-1}) and the percentage contributions to subsequent net differences in total GHG emissions reductions could be calculated individually for:

- CCS
- Energy efficiency (based on differences in TPES)
- Nuclear power
- Bioenergy (net) and
- Other renewables (wind, solar, hydro and geothermal).

All these calculations were performed and recorded in a separate MS Excel workbook, entitled "EC BCI Biomass Contributions v11.xlsx", which incorporates the functionality needed to change values of key data and assumptions. To avoid over-complication, "snapshot" results were produced for 2030 and 2050. Examples of the results for absolute contributions to net differences in total GHG emissions are shown in Table 6.9. These results are for 2030, calculated based on the 'Precautionary' approach to forest management and wood use. Results for percentage contributions, for 2030 and 2050, based on both the 'Precautionary' and 'Synergistic' approaches to forest management and wood use, are summarised in Figures 6.10 and 6.11.

The results in Table 6.9 and Figures 6.10 and 6.11 are expressed as 'GHG emissions savings' achieved under the various scenarios, compared with the Reference Scenario A. It follows that, if a specified source contributes a net difference in GHG emissions compared with Scenario A that represents a net reduction, the result is regarded as a GHG emissions saving and is expressed as a positive number. Conversely, if the contribution made by a specified source results in a net increase in GHG emissions compared with Scenario A, this is expressed as a negative number.

Table 6.9 Contributions to total GHG emissions savings in 2030 relative to Scenario A[1]

Source	Contribution by scenario[2] ($MtCO_2$-eq. yr^{-1})				
	B	**C1**	**C2**	**C3**	**D**
CCS	24	24	24	24	42
Energy efficiency	89	37	85	56	-72
Nuclear	100	135	65	86	280
Other renewables	3	74	31	73	290
Bioenergy (avoided)[3,4]	*262*	*223*	*277*	*247*	*-133*
Bioenergy (emissions)[3,5]	*-101*	*-133*	*-4*	*-71*	*101*
Bioenergy (net)[3,6]	161	90	273	176	-32
Total[7]	378	360	478	415	508

Notes to Table 6.9:

1 Results have been calculated by referring to the 'Precautionary' approach to forest management and wood use.

2 Results represent the contributions to additional GHG emissions savings achieved under the decarbonisation scenario, compared with (i.e. relative to) Reference Scenario A. Positive numbers indicate that a net reduction or saving is being contributed by the source; negative numbers indicate that a net increase is being contributed.

3 Bioenergy consists of contributions due to biomass, bioliquids, biogas and biowaste (see Section 6.9.2).

4 Results for Bioenergy (avoided) represent GHG emissions of counterfactual energy sources displaced by bioenergy.

5 Results for Bioenergy (emissions) represent biogenic CO_2 emissions and indirect GHG emissions of bioenergy, including impacts on GHG emissions related to changes in the use of material wood products and their counterfactuals.

6 Results for Bioenergy (net) represent overall or net contributions, i.e. allowing for GHG emissions of counterfactuals displaced by bioenergy, biogenic CO_2 emissions and indirect GHG emissions of bioenergy, including impacts on GHG emissions related to changes in the use of material wood products and their counterfactuals. It is calculated as the sum of the results for Bioenergy (avoided) and Bioenergy (emissions).

7 Total GHG emissions savings consist of the sum of contributions from CCS, Energy efficiency, Nuclear, Other renewables and Bioenergy (net). These results are repeated from Table 6.3 in Section 6.6 (with opposite sign, see earlier discussion), and may also be derived by taking differences based on the estimates presented in Table 6.1 in Section 6.5.2.

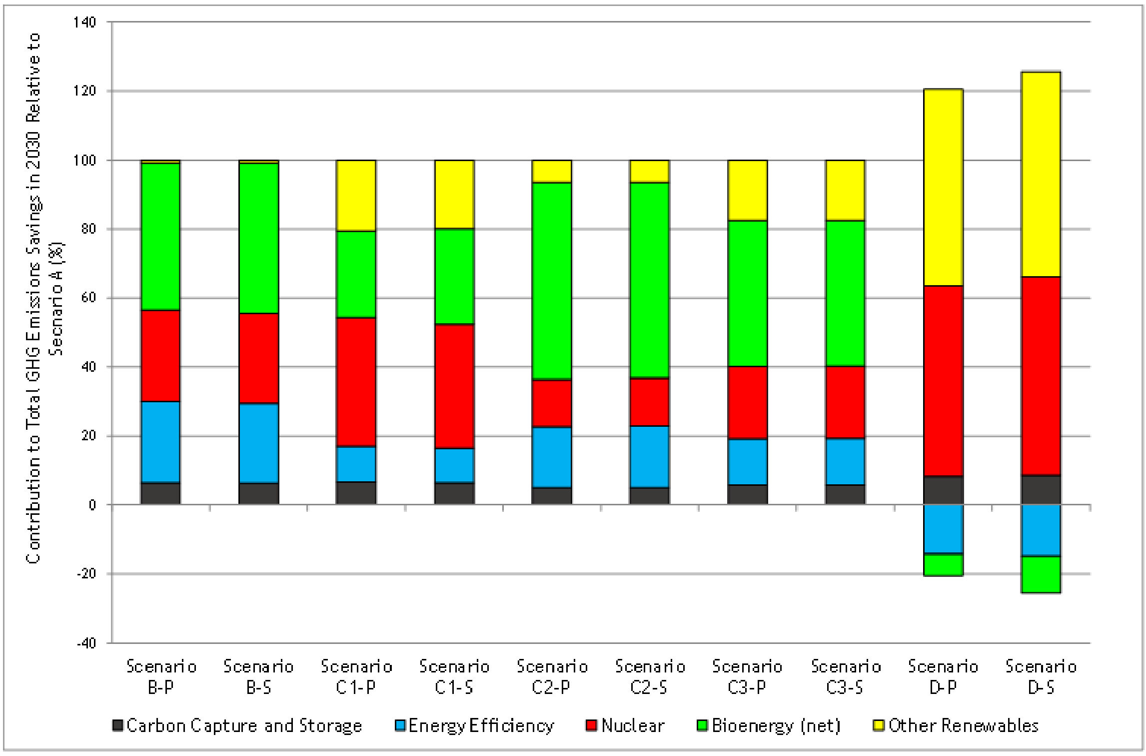

Figure 6.10. Contributions to total GHG emissions reductions in the European Union in 2030 relative to Reference Scenario A.

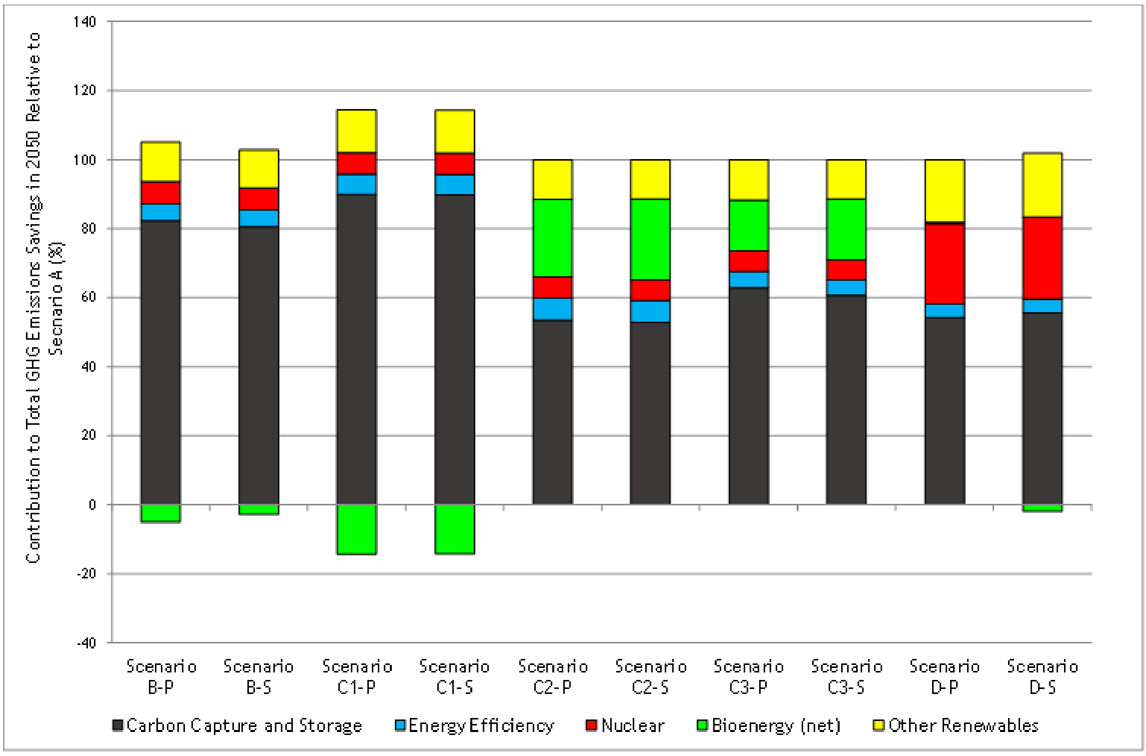

Figure 6.11. Contributions to total GHG emissions reductions in the European Union in 2050 relative to Reference Scenario A.

A number of important features are apparent from Table 6.9 and Figures 6.10 and 6.11.

Considering first of all the results for 2030 (in Table 6.9 and Figure 6.10), most crucially, taking bioenergy as a whole (i.e. as defined in Section 6.9.2), it is clear, from the results for the high-bioenergy 'carry on' scenarios, that GHG emissions associated with bioenergy use (due to changes in carbon sequestration, biogenic CO_2 emissions and indirect GHG emissions of bioenergy, including impacts on GHG emissions related to changes in the use of material wood products and their counterfactuals) are significant. However, these GHG emissions are more than outweighed by the GHG emissions avoided in these scenarios by the use of bioenergy, displacing counterfactual energy sources. Overall, under the 'carry on' scenarios (compared with Scenario A), Bioenergy (net) makes a significant contribution towards the overall net GHG emissions savings achieved, alongaide contributions due to CCS, energy efficiency, nuclear and other renewable energy sources. In contrast, under the 'Back off' Scenario D, the contribution made by bioenergy (net) in 2030 is negative (i.e. a net increase in GHG emissions due to bioenergy, compared with Scenario A). The reason for this is that, relative to Scenario A, the TPES contribution of bioenergy is lower under Scenario D, reflecting the backing off from bioenergy use in general under this scenario; in particular, backing off from biomass use, and more specifically forest bioenergy use.

A further feature of the results for Scenario D for 2030 is that the contribution to net GHG savings made by energy efficiency is negative. To understand this result, it is important to recall that the results shown in Table 6.9 and Figure 6.10 have been calculated relative to Reference Scenario A. Consequently, this result indicates that the GHG emissions savings achieved through improvements in energy efficiency are smaller in 2030 under Scenario D than under Scenario A. This outcome occurs because of detailed differences in the projected development of changes to the energy system up to 2030 under Scenario D, compared with Scenario A. For example, changes in energy efficiency (closely/specifically) associated with the higher bioenergy use under Scenario A do not happen under Scenario D. However, it should be noted that this outcome for energy efficiency under Scenario D in 2030 is an isolated result; the general trend under Scenario D is for energy efficiency to make a bigger contribution to GHG emissions savings, compared with Reference Scenario A, in part to compensate for the reduced consumption of bioenergy under Scenario D compared with Scenario A.

It is also apparent from Table 6.9 and Figure 6.10 that the specific contribution made by bioenergy to overall net GHG emissions savings under the high-bioenergy 'carry on' scenarios is variable, depending on the scenario. The contribution of bioenergy towards GHG emissions savings is highest for Scenario C2 ('Carry on/domestic crops'), and lowest for Scenario C1 ('Carry on/imported wood'). This variation has a notable influence on the total GHG emissions savings achieved by the scenarios (see Table 6.9), and is the subject of further detailed analysis, which is presented subsequently.

Now to consider the results for 2050 in Figure 6.11, one striking feature initially apparent is the significance of CCS as a contribution to the difference in total GHG emissions reductions relative to Scenarios A-P or A-S, as appropriate.

The results for 2050 also include some negative contributions to net GHG emissionsd savings, compared with Reference Scenario A. This feature is observed in Figure 6.11 for:

- Scenarios B-P and C1-P relative to scenario A-P
- Scenarios B-S, C1-S and D-S relative to scenario A-S.

These results occur because GHG emissions due to bioenergy use, arising from changes in carbon sequestration, biogenic carbon emissions and indirect GHG emissions associated with bioenergy supply, exceed the avoided the GHG emissions due to the displacement of fossil fuels by bioenergy. Put simply, this would mean that, where negative contributions to the relative differences in total GHG emissions reductions are indicated, bioenergy supply is generating more GHG emissions than the fossil fuels it replaces. This is particularly apparent for Scenarios B-P, B-S, C1-P and C1-S, all of which reflect substantial increases in the use of forest bioenergy, especially as imports from forests outside the EU27 region.

As in the case of the results for 2030, the specific contributions made by bioenergy to the overall net GHG emissions savings estimated for the high-bioenergy ‘carry on’ scenarios is variable, indeed more so in 2050.

In considering the outcomes of the above assessment of results for 2050, it will be recalled that, overall, the estimated annual total GHG emissions for all scenarios are lower than for the Reference Scenario A. This might seem to conflict with the occurrence of situations in which changes in carbon sequestration, biogenic carbon emissions and indirect GHG emissions of bioenergy supply exceed avoided GHG emissions from displaced fossil fuel combustion. The explanation for this is that substantial reductions in GHG emissions through the considerable application of CCS by 2050, as shown in Figure 6.11, more than compensate for the net increases in total GHG emissions from bioenergy supply to the EU27 region.

In the case of results for contributions made by bioenergy to GHG emissions savings in 2050, it is important to recall earlier discussions of the levels of bioenergy supply and use projected for 2050 under the high-bioenergy scenarios, particularly in the case of forest bioenergy, and issues arising from this (see Sections 4.10.4, 6.6.1 and 6.6.2).

The preceding detailed assessment of contributions made towards GHG emissions savings under the decarbonisation scenarios developed in this project has highlighted the fact that the contributions made by bioenergy are generally beneficial but are variable, depending on which scenario is considered. It is appropriate to to undertake a further, even more detailed assessment of the contributions made by bioenergy sources to GHG emissions reductions or increases. In particular, it is highly desirable to avoid circumstances in which there are net increases in total GHG emissions associated with bioenergy supply. This requires further analysis of the causes of such circumstances. Accordingly, an initial analysis was undertaken to establish the main sources contributing to total GHG emissions due to bioenergy consumption.

As already noted, bioenergy supply is defined here as consisting of various forms of biomass, including biomass derived from forests (forest bioenergy). Table 6.10 shows the percentage contributions to total GHG emissions associated with the consumption of bioenergy sources in the EU in 2030, specifically due to forest bioenergy produced in the EU27 region, Canada and the USA. These results allow for changes in carbon sequestration in forests, biogenic carbon emissions and indirect GHG emissions associated with forest bioenergy supply and use. Separate results are shown for each scenario developed in this project, based on the 'Precautionary' (P) and the 'Synergistic' (S) approaches to forest management and wood use. Table 6.11 shows similar results to Table 6.10, but for the year 2050. The results in Table 6.10 and 6.11 show that the clear majority of total GHG emissions arising from bioenergy supply to the EU in 2030 and 2050 derive from the supply of forest bioenergy, notably from within the EU27 region and from Canada and the USA. Hence, further investigation was made of the estimated net differences in GHG emissions associated with the consumption of forest bioenergy in each of the scenarios between 2010 and 2050, relative to the Reference Scenario A (A-P or A-S, as appropriate).

Table 6.10 Percentage contributions to total GHG emissions associated with all bioenergy sources, due to selected forest bioenergy sources supplied to the EU in 2030

Region	Contributions to total GHG emissions of bioenergy supply (%)									
	B		C1		C2		C3		D	
	P	S	P	S	P	S	P	S	P	S
EU	34	23	38	28	41	28	49	41	47	25
Canada	22	24	21	24	17	19	14	15	17	22
USA	19	15	19	15	15	11	12	9	15	14
Totals	**74**	**62**	**78**	**68**	**73**	**58**	**76**	**64**	**78**	**62**

Note to Table 6.10: Percentages of total GHG emissions are based on absolute values for each scenario, i.e. not relative to Reference Scenario A.

Table 6.11 Percentage contributions to total GHG emissions associated with all bioenergy sources, due to selected forest bioenergy sources supplied to the EU in 2050

Region	Contributions to total GHG emissions of bioenergy supply (%)									
	B		C1		C2		C3		D	
	P	S	P	S	P	S	P	S	P	S
EU	23	20	21	13	33	30	36	34	44	33
Canada	28	32	29	35	23	29	23	30	13	20
USA	24	21	25	23	19	18	19	18	11	11
Totals	**76**	**73**	**75**	**71**	**74**	**76**	**78**	**83**	**68**	**64**

Note to Table 6.11: Percentages of total GHG emissions are based on absolute values for each scenario, i.e. not relative to Reference Scenario A.

6.9.4. Detailed analysis of GHG emissions for forest bioenergy sources

The analysis of GHG emissions due to bioenergy sources involved the following steps:

- The relative differences in annual total GHG emissions associated with the supply of forest bioenergy sources (including material wood co-products) were calculated, for each of the decarbonisation scenarios, relative to Reference Scenario A. Separate results were calculated based on the 'Precautionary' and 'Synergistic' approaches to forest management and wood use, and for each supplying region (i.e. EU27 region, CIS region, Canada, USA and Brazil, the latter country otherwise referred to as the LAM region).
- The results from the previous step could be compared with the relative difference in the avoided GHG emissions of fossil fuels displaced by the forest bioenergy. These results were determined by combining estimated relative differences in annual forest bioenergy supply with total GHG emissions factors for the combustion of fossil fuels. Since the actual displacement of specific fossil fuels is not known from the results for scenarios produced by the VTT-TIAM model, it was necessary to explore the sensitivity of results with respect to total GHG emissions factors for a range of fossil fuels. These consisted of hard coal (representing the counterfactual giving the highest avoided GHG emissions) and natural gas (representing the counterfactual giving the lowest avoided GHG emissions). As with earlier stages of the detailed analysis described in this section, these calculations were performed and recorded in the MS Excel workbook, "EC BCI Biomass Contributions v11.xlsx".

The results of this analysis consisted of trajectories for the development over time of:

- Relative annual differences in total GHG emissions associated with the use of forest bioenergy
- Annual total avoided GHG emissions (associated with displaced fossil fuels)
- Net GHG emissions, i.e. the difference between the two previous results.

Figure 6.12 shows an example of these results for a case in which the GHG emissions due to consumption of forest bioenergy exceed the emissions avoided by displacing a fossil fuel counterfactual:

- Scenario B ('Carry on/unconstrained use')
- 'Precautionary' approach to forest management and wood use
- Fossil fuel counterfactual of natural gas.

The results in Figure 6.12 show that the net difference in GHG emissions due to the consumption of forest bioenergy (red line in Figure 6.12), as represented in Scenario B, is negligible up to about 2025. This means that the consumption of additional forest bioenergy under Scenario B, relative to the consumption projected under Reference Scenario A, does not lead to increased GHG emissions, but equally does not lead to reductions in GHG emissions. After 2025, in this example, the net difference in GHG emissions becomes increasingly positive, indicating that the consumption of additional forest bioenergy under Scenario B, relative to Reference Scenario A, leads to greatly increased GHG emissions, i.e. by 2050 total annual GHG emissions have increased by 300 $MtCO_2$-eq. yr^{-1}.

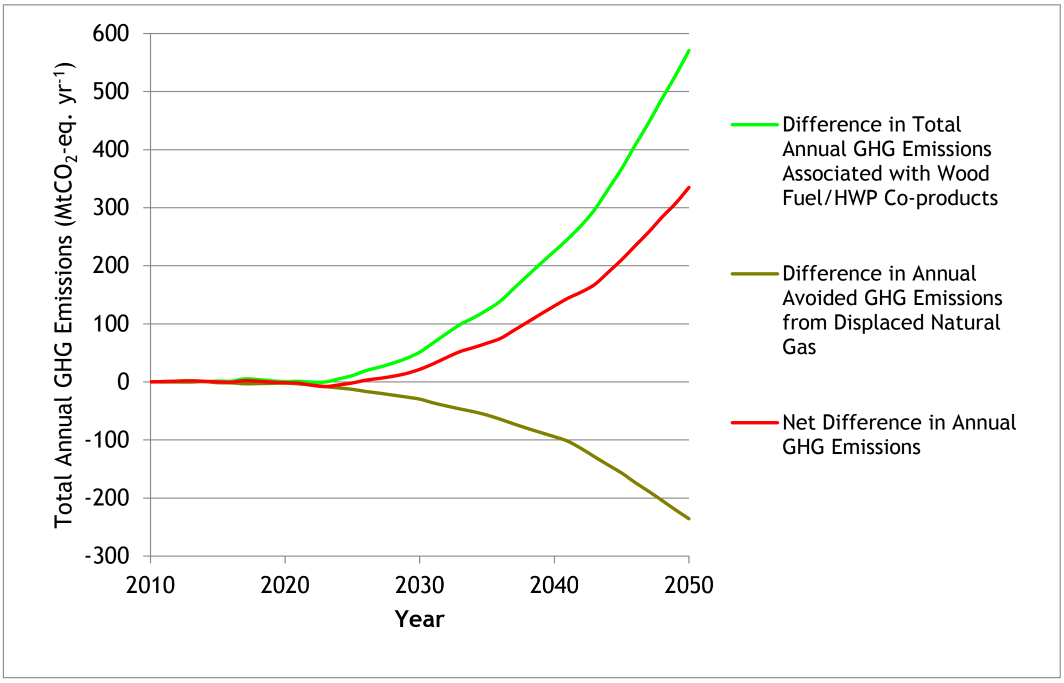

Figure 6.12. Development of annual relative difference in total GHG emissions associated with forest bioenergy use, assuming displacement of natural gas. The results are for Scenario B and the 'Precautionary' approach to forest management and wood use.

The results in Figure 6.12 represent a 'high-emissions' case, in that reference to results for either the 'Precautionary' or 'Synergistic' approach to forest management and wood use, and to the fossil fuel counterfactual, have been selected to give the highest resultant net difference in total annual GHG emissions. Alternative results can be generated for 'low-emissions' case, by an opposite selection with respect to results for either the 'Precautionary' or 'Synergistic' approach and the fossil fuel counterfactual. In this way, results could be generated for low-emissions and high-emissions cases. Taken together, these results indicate ranges for the development of the net difference in GHG emissions due to the consumption of forest bioenergy over time.

Figure 6.13 shows a summary of results for all the decarbonisation scenarios developed in this project, for the ranges in the net difference in total annual GHG emissions due to the consumption of forest bioenergy (based on the high-emissions and low-emissions emissions cases).

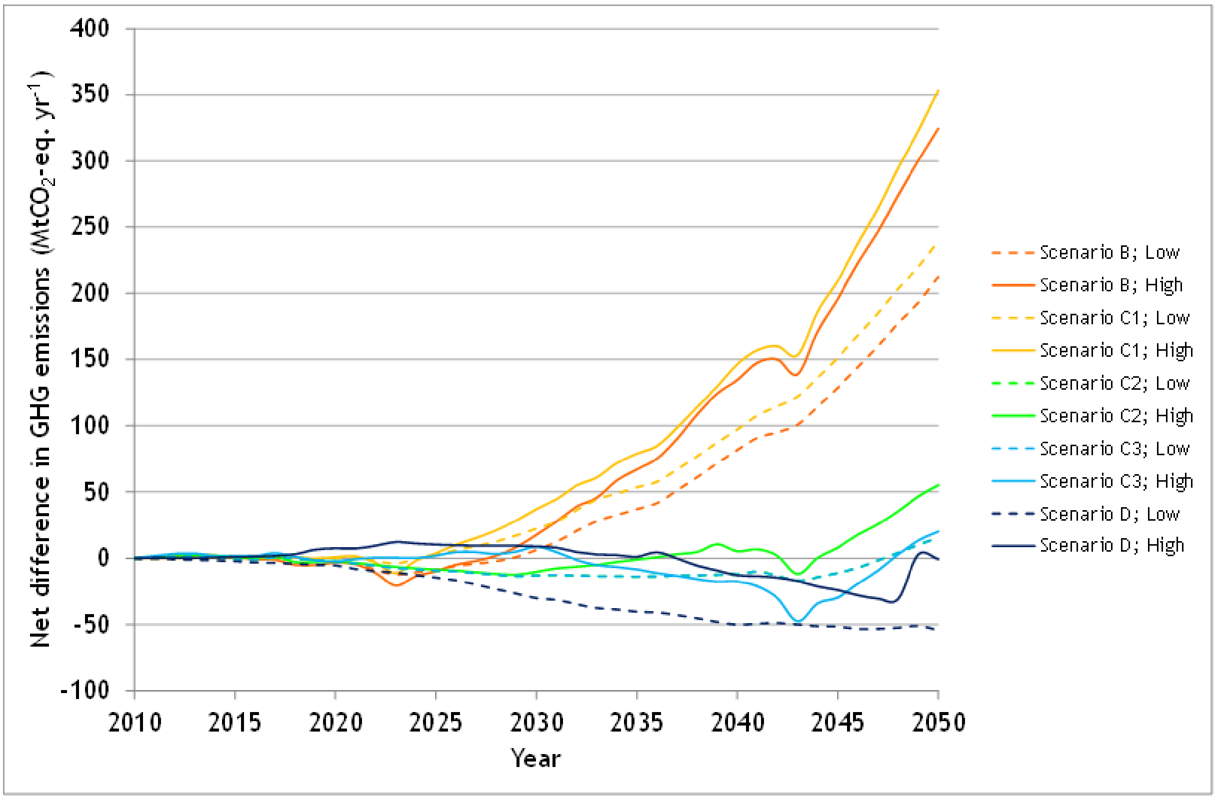

Figure 6.13. Ranges of annual net differences in GHG emissions due to forest bioenergy consumption in the EU, for the decarbonisation scenarios, relative to Reference Scenarios A-P and A-S, as appropriate.

From Figure 6.13, the following main outcomes are apparent:

- Clear and substantial increases in net differences in total GHG emissions, relative to Reference Scenario A, for forest bioenergy use under Scenarios B ('Carry on/unconstrained use') and C1 ('Carry on/imported wood')
- Slight increases or slight decreases in net differences in total GHG emissions, relative to Reference Scenario A, for forest bioenergy use under Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood')
- Clear but comparatively small decreases in net differences in total GHG emissions, relative to Reference Scenario A, for forest bioenergy use under Scenario D ('Back off').

Before drawing conclusions from the results presented in Figure 6.13, it is necessary to consider a more nuanced convention for estimating the results for all scenarios based on the 'Synergistic' approach to forest management and wood use. As explained in the preceding discussion, the calculation of net differences in GHG emissions (or in energy supply) involves calculating differences in results for each decarbonisation scenario, with respect to the Reference Scenario A. For the results presented so far in this section:

- The net differences in GHG emissions for each decarbonisation scenario, based on the 'Precautionary' approach, were calculated with respect to Reference Scenario A-P, i.e. Reference Scenario A based on the 'Precautionary' approach.

- Results for the net differences in GHG emissions for each decarbonisation scenario, based on the 'Synergistic' approach, were calculated with respect to Reference Scenario A-S, i.e. Reference Scenario A based on the 'Synergistic' approach.

Whilst these conventions have an obvious logic, it can be argued that, in calculating results for decarbonisation scenarios based on the 'Synergistic' approach, it may be more valid to refer to the Reference Scenario A for the 'Precautionary' approach. The reason for this is that Reference Scenario A, based on the 'Synergistic' approach, includes as part of its specification, exactly the same assumptions as made in the decarbonisation scenarios based on the 'Synergistic' approach, with regard to additional measures aimed at:

- Conserving and enhancing forest carbon stocks (and sequestration) as a complement to additional forest bioenergy supply
- Favouring co-production and effective use (and disposal) of material wood products in conjunction with additional forest bioenergy supply.

However, the rationale behind the definition of the 'Synergistic' approach was to permit the assessment of the sensitivities of the outcomes for scenarios, in terms of impacts on GHG emissions, due to approaches taken to forest management and wood use. Specifically, the various project scenarios (including Reference Scenario A), in combination with the 'Synergistic' approach, are intended to indicate the potential of additional measures, taken in explicit conjunction with increased wood production, to support the supply of forest bioenergy with low associated GHG emissions. Crucially, no relevant supporting measures are currently in place as part of existing policies (which have set the targets for renewable energy sources for 2020, represented by Reference Scenario A). It follows that Reference Scenario A in combination with the 'Synergistic' approach in itself represents a change from current policies. Indeed, it may be noted that a comparison of the main project results for Reference Scenario A based on the 'Synergistic' approach, with the results for Scenario A based on the 'Precautionary' approach, enables the assessment of the potential for additional measures to support the delivery of existing policies with respect to renewable energy sources, especially bioenergy sources, with low associated GHG emissions.

Based on the above discussion, a comparison of results for decarbonisation scenarios based on the 'Synergistic' approach, with results for Reference Scenario A based on the 'Precautionary' approach, would seem appropriate. At the same time, it must be acknowledged that a much more debatable point concerns the exact nature of any practical instruments aimed at achieving an explicit link between increased forest bioenergy consumption, and the types of supporting measures indicated in the above discussion, and how realistically such an outcome might be achieved.

The results in Figure 6.14 illustrate the potential contributions of additional supporting measures, taken in conjunction with increased forest bioenergy supply, as represented by the 'Synergistic' approach to forest management and wood use. To produce these estimates, the contributions due to forest bioenergy supplied from the CIS region, Canada, the USA and Brazil have been calculated in exactly the same way as in Figure 6.13, i.e. with respect to Reference Scenario A-S, based on the 'Synergistic' approach. In contrast, the contributions due to forest bioenergy supplied from within the EU27 region have been calculated with respect to Reference Scenario A-P, based on the 'Precautionary' approach. Essentially, this means that the results represent the potential for additional supporting measures to be taken in the EU27 region only. The differential treatment of results for the EU27 and other regions may be considered to be a conservative approach, also acknowledging considerable uncertainty with regard to the potential for supporting measures to be taken outside the EU region. In all cases, the fossil fuel counterfactual was natural gas.

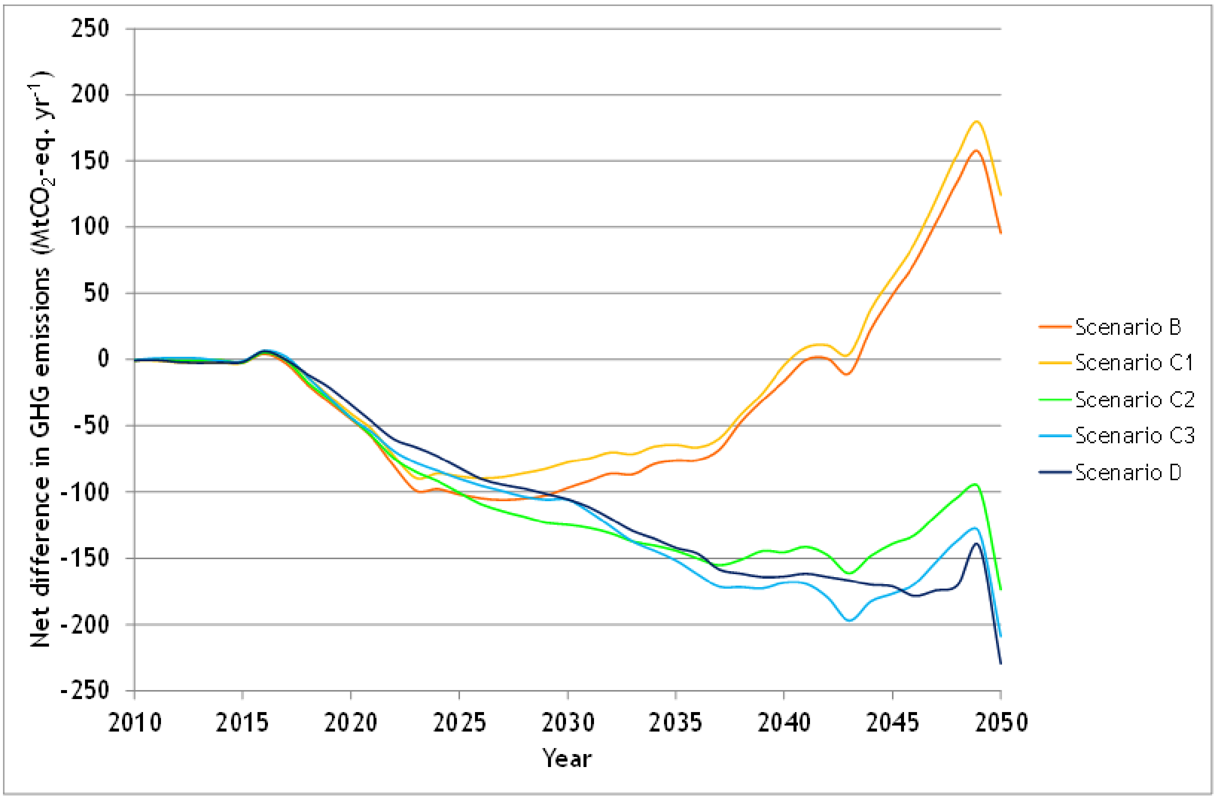

Figure 6.14. Annual net differences in GHG emissions due to forest bioenergy consumption in the EU, for the decarbonisation scenarios ('Synergistic' approach), but with results for supply from the EU27 region calculated relative to Reference Scenario A-P. A fossil fuel counterfactual of natural gas has been assumed for all forest bioenergy use.

From Figure 6.14, the following main outcomes are apparent:

- Clear and substantial decreases then increases in net differences in total GHG emissions, relative to Reference Scenario A, for forest bioenergy use under Scenarios B ('Carry on/unconstrained use') and C1 ('Carry on/imported wood')
- Clear and substantial decreases in net differences in total GHG emissions, relative to Reference Scenario A, for forest bioenergy use under Scenarios C2 ('Carry on/domestic crops'), C3 ('Carry on/domestic wood') and Scenario D ('Back off').

A notable feature in both Figures 6.13 and 6.14 is a pronounced increase in the annual net differences in GHG emissions for Scenarios B and C1 after 2030. Smaller but equally notable increases occur in Figure 6.11 for Scenarios C2 and C3 after 2040. The causes of such increases have been discussed in Sections 4.10.6, 6.6 and 6.7. In particular, the pronounced increases in forest bioenergy consumption (and therefore supply), from some point after 2030 up to 2050, as represented to varying degrees in all of the high-bioenergy scenarios have been identified as likely to lead to significant biogenic carbon emissions.

Table 6.12 summarises results for annual net differences in GHG emissions due to forest bioenergy use in 2030, for the various decarbonisation scenarios relative to Reference Scenario A. Table 6.13 shows similar results but for the year 2050. The main estimates in these tables have been derived by taking the average of the low and high results in Figure 6.13, for each scenario, for the relevant year. The ranges on these estimates have been derived as the half-differences of the low and high estimates for each scenario for the relevant year in Figure 6.13. A further set of estimates is shown in Tables 6.12 and 6.13, based on the trajectories for annual net differences in GHG emissions as shown for each scenario in Figure 6.14. These estimates give an indication of the potential influence on the GHG emissions associated with forest bioenergy, as represented in the scenarios, due to additional supporting measures with regard to forest management and utilisation of harvested wood.

The results in Tables 6.12 and 6.13 are expressed as 'GHG emission savings' contributed by forest bioenergy under the various scenarios, compared with Reference Scenario A. It follows that, if forest bioenergy contributes a net difference in GHG emissions compared with Scenario A that represents a net reduction, the result is regarded as a GHG emissions saving and is expressed as a positive number. Conversely, if the contribution made by forest bioenergy results in a net increase in GHG emissions compared with Scenario A, this is expressed as a negative number. Presenting the results in this way permits comparisons to be made with the results of the previous assessment of GHG emissions savings contributed by various sources (see Table 6.9 and Figures 6.10 and 6.11 in Section 6.9.3). However, it should be noted that this means that the results in Tables 6.12 and 6.13 take the opposite sign to those presented in Figures 6.13 and 6.14.

Tables 6.12 and 6.13 also include the results for the overall GHG emissions savings achieved by each scenario relative to Scenario A, to facilitate the comparison with the results for forest bioenergy. In Table 6.11, a further set of results is included for Bioenergy (net), as presented earlier in Table 6.11 in Section 6.9.3, i.e. the GHG emsisions savings contributed by all bioenergy sources, as defined in Section 6.9.2.

Table 6.12 Contributions to total GHG emissions savings in 2030 relative to Scenario A, highlighting the contribution due to forest bioenergy

Scenario	Net GHG emissions savings[1] ($MtCO_2$-eq. yr^{-1})				
	Contribution of forest bioenergy			Bioenergy (net)[4,5]	Total (all sources)[6]
	Estimate[2]	Range[2]	With additional supporting measures[3]		
B	-12	±6	97	161	378
C1	-30	±7	77	90	360
C2	12	±1	125	273	478
C3	3	±12	106	176	415
D	11	±20	105	-32	508

Notes to Table 6.12:

1 Results represent the contributions to additional GHG emissions savings achieved under the decarbonisation scenario, compared with (i.e. relative to) Reference Scenario A. Positive numbers indicate that a net reduction or saving is being contributed by the source; negative numbers indicate that a net increase is being contributed.

2 Results have been calculated by referring to the estimates for 2030 in Figure 6.13, changing their sign (see earlier discussion).

3 Results have been calculated by referring to the estimates for 2030 in Figure 6.14, changing their sign (see earlier discussion).

4 Bioenergy consists of contributions due to biomass, bioliquids, biogas and biowaste (see Section 6.9.2).

5 Results for Bioenergy (net) represent overall or net contributions, i.e. allowing for GHG emissions of counterfactuals displaced by bioenergy, biogenic CO_2 emissions and indirect GHG emissions of bioenergy, including impacts on GHG emissions related to changes in the use of material wood products and their counterfactuals. These results are repeated from Table 6.9 in Section 6.9.3.

6 Total GHG emissions savings consist of the sum of contributions from CCS, Energy efficiency, Nuclear, Other renewables and Bioenergy (net). These results are repeated from Table 6.3 in Section 6.6 (with opposite sign, see earlier discussion) and Table 6.9 in Section 6.9.3, and may also be derived by taking differences based on the estimates presented in Table 6.1 in Section 6.5.2.

When compared with the overall GHG emissions savings in 2030, as estimated for each scenario, the main results in Table 6.12 indicate that, in the absence of additional measures to support positive forest management and wood use with regard to GHG emissions:

- The unconstrained use of forest biomass for energy (Scenario B) contributes a small net increase in GHG emissions in 2030. This represents an offsetting of approximately 3% to the overall net GHG emissions saving of 378 $MtCO_2$ yr^{-1} achieved in 2030, relative to Scenario A. The offsetting to the overall net GHG emissions saving due to sources of bioenergy is approximately 7%.

- The increased use of forest biomass for energy, emphasising the use of imported forest bioenergy, also relatively unconstrained (Scenario C1), contributes a moderate net increase in GHG emissions in 2030. This represents an offsetting of approximately 8% to the overall net GHG emissions saving of 361 $MtCO_2\ yr^{-1}$ achieved in 2030, relative to Scenario A. The offsetting to the overall net GHG emissions saving due to sources of bioenergy is approximately 25%.
- The increased use of forest biomass for energy, emphasising the use of domestic agricultural biomass for energy (Scenario C2) contributes a small net decrease in GHG emissions in 2030. This represents an enhancement of approximately 3% to the overall net GHG emissions saving of 478 $MtCO_2\ yr^{-1}$ achieved in 2030, relative to Scenario A. The enhancement to the overall net GHG emissions saving due to sources of bioenergy is approximately 5%.
- The increased use of forest biomass for energy, emphasising the use of domestic forest bioenergy (Scenario C3) contributes a small net decrease in GHG emissions in 2030. This represents an enhancement of approximately 1% to the overall net GHG emissions saving of 415 $MtCO_2\ yr^{-1}$ achieved in 2030, relative to Scenario A. The enhancement to the overall net GHG emissions saving due to sources of bioenergy is approximately 2%.
- When the use of forest biomass for energy is deprioritised relative to Scenario A (Scenario D), the reduced consumption of forest bioenergy contributes a small net decrease in GHG emissions in 2030. This represents an enhancement of approximately 2% to the overall net GHG emissions saving of 509 $MtCO_2\ yr^{-1}$ achieved in 2030, relative to Scenario A. The reduced consumption of forest bioenergy in Scenario D, relative to Scenario A, leads to a net increase in GHG emissions due to the reduced consumption of bioenergy in general being smaller than it otherwise would have been under Scenario D, by approximately 26%.
- In general, the impacts of increasing or decreasing consumption of forest bioenergy on the GHG emissions savings achieved in 2030, as represented in the scenarios developed in this project, are quite marginal. A notable exception is Scenario C1, in which the (relatively unconstrained) use of imported forest bioenergy is emphasised, for which forest bioenergy contributes a moderate net increase in GHG emissions in 2030.

The further set of results in Table 6.12 for forest bioenergy, representing the potential impacts of additional measures to support positive forest management and wood use, indicates that these can have very strong positive impacts on the GHG emissions savings in 2030 achieved through the use of bioenergy, notably forest bioenergy.

Table 6.13 Contributions to total GHG emissions savings in 2050 relative to Scenario A, highlighting the contribution due to forest bioenergy

Scenario	Net GHG emissions savings[1] ($MtCO_2$-eq. yr^{-1})			
	Contribution of forest bioenergy			Total (all sources)[4]
	Estimate[2]	Range[2]	With additional supporting measures[3]	
B	-269	±56	-96	1 179
C1	-296	±57	-125	1 222
C2	-35	±20	174	1 624
C3	0	±20	209	1 594
D	27	±27	229	1 905

Notes to Table 6.13:

1 Results represent the contributions to additional GHG emissions savings achieved under the decarbonisation scenario, compared with (i.e. relative to) Reference Scenario A. Positive numbers indicate that a net reduction or saving is being contributed by the source; negative numbers indicate that a net increase is being contributed.

2 Results have been calculated by referring to the estimates for 2050 in Figure 6.13, changing their sign (see earlier discussion).

3 Results have been calculated by referring to the estimates for 2050 in Figure 6.14, changing their sign (see earlier discussion).

4 Total GHG emissions savings consist of the sum of contributions from CCS, Energy efficiency, Nuclear, Other renewables and Bioenergy (net). These results may be derived by taking differences based on the estimates presented in Table 6.1 in Section 6.5.2.

When compared with the overall GHG emissions savings in 2050, as estimated for each scenario, the main results in Table 6.13 indicate that, in the absence of additional measures to support positive forest management and wood use with regard to GHG emissions:

- The unconstrained use of forest biomass for energy (Scenario B), or the increased use of biomass for energy, emphasising the use of imported forest bioenergy (also relatively unconstrained, Scenario C1), contributes a substantial net increase in GHG emissions in 2050. This represents an offsetting of approximately 24% to the overall net GHG emissions saving of about 1 200 $MtCO_2$ yr^{-1} achieved in 2050, relative to Scenario A.

- The increased use of forest biomass for energy, emphasising the use of domestically produced biomass (from agricultural or forest sources, Scenarios C2 and C3) contributes a negligible or small net increase in GHG emissions in 2050. This represents an offsetting of approximately zero to 2% to the overall net GHG emissions saving of about 1 600 $MtCO_2$ yr^{-1} achieved in 2050, relative to Scenario A.

- When the use of forest biomass for energy is deprioritised (Scenario D), bioenergy contributes a small net saving in GHG emissions in 2050. This represents an enhancement of approximately 1% to the overall net GHG emissions saving of 1 905 $MtCO_2$ yr^{-1} achieved in 2050, relative to Scenario A.

The further set of results in Table 6.12 for forest bioenergy, representing the potential impacts of additional measures to support positive forest management and wood use, indicates that such measures:

- Would not completely mitigate net increased in GHG emissions in 2050 associated with the unconstrained use of forest biomass for energy (Scenario B), or the increased use of biomass for energy, emphasising the use of imported forest bioenergy (Scenario C1)
- Can have strong positive impacts on GHG emissions reductions achieved through the use of domestically-produced bioenergy sources (Scenarios C2 and C3), notably in the case of forest bioenergy.

The main results in Tables 6.12 and 6.13 require careful interpretation, since the results have been derived on a relative basis to the Reference Scenario A. The basis of their calculation is therefore different to the results considered in Sections 6.4 to 6.8, which have been calculated on an absolute basis and permit the assessment of individual scenarios in isolation. If this is taken into account, the results in Tables 6.12 and 6.13 may be interpreted as indicating outcomes that are consistent with the earlier assessments of the final project results, including with regard to the detailed contributions made by bioenergy to GHG emissions, as already considered in Sections 6.6, 6.7 and 6.9.3, specifically:

- A distinction is exhibited amongst the scenarios in terms of reductions achieved in GHG emissions, with scenarios emphasising the unconstrained use of bioenergy, or the (relatively unconstrained) use of imported forest bioenergy achieving the smallest reductions, as opposed to scenarios emphasising the use of domestically-produced bioenergy, or the de-prioritisation of bioenergy achieving the biggest reductions.
- For the high-bioenergy 'Carry on' Scenarios, pronounced increases in projected forest bioenergy use from some point after 2030 up to 2050 lead to relatively high GHG emissions, which detract to an extent from the achievement of overall reductions in total GHG emissions.

As explained in Sections 6.6 and 6.7, there are a number of reasons for the distinctions exhibited amongst the scenarios as modelled in this quantitative assessment, notably differences in assumptions about forest management approaches, subsequent biogenic carbon emissions, types of feedstock for forest bioenergy, interactions with material wood products and their associated counterfactuals, and end-of-life disposal pathways for material wood products. It is important to appreciate that there is an intimate linkage between the outcomes reported as the main results of this project and the underlying assumptions.

In both Tables 6.12 and 6.13, the results indicate that the potential impacts of additional supporting measures are significant, leading to very substantial net decreases in GHG emissions associated with forest bioenergy use in 2030, for all scenarios. Such additional supporting measures would aim to encourage appropriate approaches to production and use of wood, and the conservation and enhancement of management of forest carbon stocks, explicitly linked to increased forest bioenergy supply. However, it must be stressed that such outcomes would only occur and, strictly, would only be "attributable" to the supply and consumption of the forest bioenergy, if the additional supporting measures were taken in explicit conjunction with the increased bioenergy supply, and in the event that such an approach could be effective. It may be further noted from the results in Tables 6.12 and 6.13 that the potential magnitude of the contribution due to such additional supporting measures is so significant that their impacts on GHG emissions due to the use of forest bioenergy could be effective, even if the potential of such measures was only partially realised. The practicality of measures aimed at positive approaches to forest management and wood use is considered briefly in Section 7.4.5.

The preceding assessment, based on Table 6.9 and Figures 6.10 and 6.11, and on Figures 6.13 and 6.14 and Tables 6.12 and 6.13, leads to several conclusions that support and elaborate the findings presented in Sections 6.5 to 6.7, specifically:

Overall, under the 'Carry on' Scenarios (compared with Scenario A), the net impact of bioenergy is a significant contribution towards the overall net GHG emissions savings achieved in 2030, alongside contributions due to other sources (CCS, energy efficiency, nuclear and other renewable energy sources). In contrast, under the 'Back off' Scenario D, the reduced consumption of bioenergy in general leads to a net increase in GHG emissions in 2030.

The contributions made by bioenergy towards net GHG emissions savings in 2030 are generally beneficial. However, the detailed contributions are variable, depending on the scenario. The contribution of bioenergy towards GHG emissions savings is higher for scenarios emphasising bioenergy supply from domestic sources and lower for scenarios emphasising consumption of imported forest bioenergy and/or the relatively unconstrained use of bioenergy sources.

In order to reduce risks of net increases in GHG emissions associated with forest bioenergy use, the increases in levels of consumption of imported forest bioenergy after 2030 suggested by the high-import scenarios developed in this project should be avoided, unless additional supporting measures can be applied to ensure that increased production of forest bioenergy leads to overall positive impacts on GHG emissions.

The assessment supports earlier conclusions regarding risks associated with the high levels of forest bioenergy consumption, as represented in the 'Carry on' Scenarios from some point after 2030, particularly as represented in scenarios by 2050.

The assessment highlights the importance of additional measures to support positive forest management and wood use in terms of GHG emissions. Such measures can reduce risks of high GHG emissions and underpin and/or enhance the positive impacts on GHG emissions associated with forest bioenergy use. As part of any such additional supporting measures, it is important to address potential interactions with the production and consumption of material wood products. For example, this could involve favouring the co-production of forest bioenergy in conjunction with additional material wood products, *targeting the displacement of GHG-intensive counterfactual products, and encouraging the disposal of wood products at end of life with low impacts on GHG emissions.*

6.10. Refined scenario for bioenergy use in the EU up to 2030

The analysis in Sections 6.4 to 6.9 has thoroughly assessed the final project results for the six scenarios for bioenergy consumption in the EU developed in this project, particularly in terms of potential impacts on GHG emissions. It has been possible to identify positive and negative features in the various scenarios, which suggests the possibility of designing a more optimised scenario, based on a combination of the characteristics of the original scenarios, and informed by existing policy targets for renewable energy for 2030. The following discussion tentatively proposes a description of such a possible scenario, in terms of a number of key building blocks. The design of the building blocks has been informed by the assessment of the six scenarios developed in this project, taking into consideration:

- A requirement for agricultural biomass production for energy within the EU27 region not to incur significant risks of iLUC
- A requirement to produce forest biomass within the EU27 region for use as energy, without approaching the limits of sustainable-yield supply, whilst limiting negative impacts on the soil nutrient status of forest sites, and without causing significant diversion of wood supply from use for material wood products to use for energy
- A requirement to produce forest biomass in regions outside the EU region for use as energy within the EU region, without approaching the limits of sustainable-yield supply, whilst limiting negative impacts on the soil nutrient status of forest sites, and without causing significant diversion of wood supply from use for material wood products to use for energy
- An aim of ensuring the minimisation or mitigation of biogenic carbon emissions associated with the increased production and supply of forest biomass from all geographical regions, for consumption as energy within the EU region.

It should be noted that such a refined scenario could be subjected to an assessment of GHG impacts, as undertaken for the agreed scenarios developed in this project.

6.10.1. Building block 1: 2030 target for bioenergy use

As highlighted in Section 6.9.1, the modelling of the scenarios developed in this project simulated the potential development of a range of possible renewable energy sources, not just bioenergy, and also represented measures aimed at improved energy conversion and efficiency. Noting that the Climate and Energy Policy Framework specifies that “an EU target of at least 27% is set for the share of renewable energy consumed in the EU in 2030” (European Council, 2014), an assessment presented in Section 6.9.2 indicated that the scenarios modelled in this project are consistent with meeting or exceeding such a target (when final energy consumption is considered). Furthermore, the high-bioenergy ‘Carry on’ Scenarios modelled in this project typically involve contributions from bioenergy (as defined in the VTT-TIAM model, see Section 6.9.2) to final energy consumption of about 17% to 18%, and to TPES of about 14% to 15%. This equates to a contribution made by primary sources of biomass (not including black liquor, see Section 6.9.2) of about 10% to 11%. Consequently, a refined scenario might involve setting a target for primary biomass sources to contribute about 11% to TPES in 2030, or about 160 Mtoe, according to the simulations of the VTT-TIAM model for the high-bioenergy scenarios developed in this project.

(Note that this target for the supply of primary sources of biomass involves the assumption, based on the results of the VTT-TIAM model simulations, that the remainder of the 14% to 15% target for bioenergy to contribute to TPES may be met through contributions made by biowaste, biogas, black liquor and imported bioliquids.)

6.10.2. Building block 2: 2030 target for supply of agricultural biomass

The supply of biomass for energy from agricultural sources is assumed to involve supply from primarily within the EU27 region. A target or limit for the supply of agricultural bioenergy sources could be set within the range suggested for 2030 under Scenarios C2 ('Carry on/domestic crops') or C3 ('Carry on/domestic wood').

Based on the discussion in Section 3.7.2, in particular Figure 3.12, this implies a target of between roughly 75 Mtoe yr^{-1} and roughly 105 Mtoe yr^{-1}. Approximately 30% of this target may be met through establishing an area of perennial energy crops in the EU of between roughly 3.2 Mha and roughly 7.1 Mha, respectively (see Sections 4.9.1 and 4.9.2). There would also be a smaller contribution from annual energy crops, but the quantities and areas involved would be less than in 2010. It should be noted that these projections for areas of crops supplying bioenergy have been calculated allowing explicitly for the avoidance of iLUC (see Section 3).

The main contribution to agricultural biomass used for energy would be made through the removal and use of agricultural residues. In the case of straw removal, very approximately, this would involve the removal of residues, annually, from around 41 to 55 Mha of agricultural land. A further, smaller contribution would be made from other sources of agricultural residues such as arboricultural arisings.

6.10.3. Building block 3: 2030 target for supply of forest biomass for energy

Having established the 2030 target for bioenergy supplied from agricultural sources, the target or limit for the supply of forest biomass for energy could be determined as the remainder required to meet an overall target or limit for biomass supply in the EU27 region. Based on Building block 1, which suggests a contribution to TPES in 2030 due to biomass of around 11%, or roughly 160 Mtoe yr^{-1}, and the numbers for agricultural biomass from Building block 2, this suggests a level of supply of forest biomass between 55 to 85 Mtoe.

6.10.4. Building block 4 (option 1): 2030 relative balance of supply of forest bioenergy from domestic and imported sources

The assessment of the results presented earlier indicates that there may be significant risks of increased GHG emissions, rather than reductions, associated with the use of forest bioenergy from some imported sources. Hence, to ensure the supply of forest bioenergy, whilst reducing risks of increases in GHG emissions, a balance could be found between the supply from domestic and imported sources. An appropriate balance for 2030 seems to be that represented in Scenarios C2 ('Carry on/domestic crops') or C3 ('Carry on/domestic wood'). This would imply limiting the supply of forest biomass explicitly for use as energy in the EU27 region from imported sources in 2030 to roughly around 20 Mtoe yr^{-1}. However, there may be significant practical obstacles to placing limits on levels of imported forest biomass, for use as energy or for any other purpose. An alternative approach might involve requiring consumers to limit the use imported forest bioenergy sources to no more than (roughly) 25% to 35% of total forest bioenergy use by energy content (the percentage depends on the overall contribution of forest bioenergy, see Section 6.10.2). The definition of "consumers" in this context is left open, and could refer, for example, to EU Member States or energy-generating installations. This approach also presents difficulties, since some consumers will find it very easy to keep within such a target, whilst others will find it impossible. One possible solution could involve adopting an 'effort sharing' principle, e.g. allocating different percentages for use of imported forest bioenergy, perhaps depending on the regional potential for domestic supply of (forest) bioenergy, such that a target of around 25% to 35% is still achieved overall for the EU. The targets could be expressed equally well in terms of the contributions made by domestic (EU) forest bioenergy supplies, e.g. requiring 65% to 75% of total supply of forest bioenergy to be from EU sources (roughly 35 to 65 Mtoe yr^{-1}).

It is difficult to estimate the areas of forest likely to be involved in the supply of the levels of forest bioenergy indicated by the above proposals. However, very tentatively and approximately:

- In the EU27 region, between 40 and 55 Mha of forest may be involved. This represents approximately 30% of the forest area classified as available for wood production in the EU27 region
- In regions importing forest biomass to the EU, taken to be Canada, the USA, and to a much lesser extent the CIS region, and assuming that new biomass plantations in Brazil do not contribute to the supply, about 45 Mha of forest may be involved. This represents approximately 7% of the forest area classified as available for wood production in these regions. However, the details vary considerably between regions/countries. The quantities of biomass supplied by the regions identified earlier, and the forest areas involved, could be reduced if a viable and significant contribution were to be made from new plantation forests established in Brazil (see Section 4.8.2). However, currently, it is difficult to assess the feasibility and likelihood of such a contribution, as well as the associated impacts on carbon sequestration, GHG emissions and wider environmental factors.
- In the EU27 region, it is likely that the main sources of forest bioenergy will be produced by increasing extraction of biomass from forest areas already under

management for wood production. (The area of such forests may perhaps represent 70% of the area involved in forest bioenergy production.)

- In regions importing forest biomass to the EU, there could be more emphasis on producing forest bioenergy by introducing management for production in areas where previously this was not practiced, which would need to involve co-production of material wood products alongside forest bioenergy. However, there is considerable uncertainty with regard to the details of the forest management practices in regions outside the EU that would be involved in the supply of forest bioenergy.

Apart from their somewhat speculative and tentative nature, it is important to correctly understand and interpret the estimates for areas suggested above, most notably (see Section 2.3 of the Task 1 report for this project):

- Typically, the production of biomass from the forest areas would take place periodically, not annually
- Many harvesting operations in forests would involve thinning rather than felling of forest stands, meaning that only some of the biomass would be harvested from the forest areas in these cases
- It is likely that, in practice, the forest stands involved in the supply of forest bioenergy would 'rotate', involving a total forest area larger than suggested by the estimates indicated
- Apart from exceptional circumstances, the harvesting/extraction of biomass from forests would be for a range of uses, e.g. normally involving co-production of wood for material products, therefore the areas identified are not producing forest bioenergy exclusively
- As highlighted in Section 4.8.3, where forest areas have been identified as involved in increased production of biomass for use of bioenergy, in the case harvest residues, this does not mean that 100% of the available residues are harvested over this area. Typically, the potential assumed in the modelling underpinning the assessment in this project varied between 30% and 50%.

6.10.5. Building block 4 (option 2): Strong sustainability criteria applied to both domestically-produced and imported forest bioenergy to ensure GHG emissions reductions

An alternative to setting a balance between the supply of forest bioenergy from imported and domestically-produced sources (see Section 6.10.4) would be to further clarify whether there are significant variations in sources of imported forest bioenergy, in terms of low or high risks to GHG emissions. For example, more detailed assessments could be made of potential forest bioenergy sources in different regions, and the scope for options for different approaches to forest management. As an example, refined estimates of GHG emissions associated with forest bioenergy produced in Canada might distinguish variations with regard to biomass production from forest areas:

- Already under management for production (also considering the types of practice involved, e.g. early thinnings, extraction of harvest residues)
- Brought into management for production where previously this was not planned
- Previously subjected to significant natural disturbance, with the possibility of salvage logging
- Involving/not involving co-production of forest bioenergy in conjunction with material wood products.

The outcome of such an analysis could be used to inform sustainability criteria attached to all sources of forest bioenergy, regardless of their geographical origin, and could also inform the design of additional supporting measures as considered in Building block 6, Section 6.10.7.

6.10.6. Building block 5: levels of biomass use after 2030

The assessment of the results presented earlier indicates a case for avoiding setting targets that would further increase the levels of supply of biomass for energy (all sources) in the EU after 2030. This position could be reviewed, if a future assessment and strong evidence indicates that higher levels of supply can be achieved without incurring increases in GHG emissions and within the limits of sustainable-yield production.

6.10.7. Building block 6: additional supporting measures 2030

Regardless of the approach taken to Building block 4, the assessment of the results presented earlier strongly indicate a case for explicitly linking the supply/consumption of bioenergy, particularly forest biomass for energy, to supporting measures aimed at ensuring low associated GHG emissions. These measures could possibly include:

- A requirement for commitments to be made by proponents of significant new forest bioenergy projects (perhaps on the scale of several tens of megawatts) in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved. As explained in Section 2.3.23, this would require *strategic assessment*, of the total GHG emissions impacts of commercial decisions involving major changes in activities that will lead to increased consumption of forest bioenergy, in principle similar to the assessment of policies.
- The use of a decision-tree approach for initial screening of sources of bioenergy (see tentative example for forest bioenergy in Figures 2.1a to 2.1d, Section 2.4).
- Favouring the co-production of forest bioenergy in conjunction with additional material wood products, targeting the displacement of GHG-intensive counterfactual products, and encouraging the disposal of wood products at end of life with low impacts on GHG emissions.
- Encouraging the positive management of vegetation carbon balances as part of initiatives aimed at increasing the supply/consumption of bioenergy, e.g. for forest

bioenergy, this could involve afforestation activities and the enrichment of degraded forest stands to enhance carbon stocks and productive potential. This may be easier to achieve where the land areas involved within the EU region. However, extension to other regions may be possible if explicitly linked to requirements placed on consumers of bioenergy. Note that, in this project, the area of land available for afforestation without incurring significant risks of iLUC has been estimated at between 6 and 8 Mha (Table 4.4, Section 4.7.2).

6.11. Limitations of this assessment

In considering the quantitative assessment presented in Sections 3 to 6 of this report, and the conclusions presented subsequently in Section 7, it is important to bear in mind that, like any such study, this this project and its conclusions are dependent on the validity of the assumptions made in developing scenarios and the associated modelling. These have been discussed in detail in Sections 2 to 5 of this final project report. It is also the case that LCA studies such as carried out in this project are subject to certain limitations and uncertainties, some of which relate to the underlying assumptions. Key limitations have been highlighted at relevant points throughout this report and these are repeated and elaborated below.

6.11.1. The scenarios are not designed to predict an outcome for a 'most likely' future development of energy use in the EU

The scenarios developed in this study aim to illustrate the effect of different options related to biomass consumption for bioenergy on GHG emissions, including biogenic carbon emissions. As such, the scenarios are not intended to be a prediction of the future use of biomass for energy and related GHG emissions, since, especially for the longer time scales up to 2050, projections become very uncertain. However, it is one of the specific purposes of this project to investigate the impacts on GHG emissions of different possible paths for the future development of the consumption of biomass for energy. In this context, a prediction of a most likely outcome is of less interest, compared with a range of possible scenarios, as considered in this project. Hence, from the perspective of the consequential LCA study undertaken here, the aim has been to determine a suite of scenarios, each of which represents a set of contrasting actions, which might be adopted in taking forward policies towards bioenergy in the EU. The scenarios should thus illustrate the potential sensitivity of impacts in terms of GHG emissions due to different approaches to encouraging (or indeed discouraging) the use of biomass for energy in the EU.

6.11.2. The scenarios represent a small selection out of many possibilities

Noting the discussion in the previous paragraph, it should be stressed that the six scenarios developed in this project constitute a small set out of very many possibilities for the future development of EU policies towards energy, especially bioenergy. The consideration of more scenarios was not possible within the scope of this current project. However, the six scenarios covered in this project were the subject of careful consultation and agreement with the Commission, and should represent the major distinctions amongst possible scenarios for future bioenergy use in the EU.

6.11.3. There are limitations in the modelling approaches

As described in Section 3 and explored further in Section 6.9.1, as part of the development of the scenarios considered in this project, the VTT-TIAM model was applied to simulate the supply and final consumption of biomass for energy, including the conversion technologies involved. The VTT-TIAM model was also used to estimate the cost performance of the scenarios, as described in Section 6.9, as well as some of the GHG emissions associated with energy use, as explained in Section 6.9.1. Scenario-based and model-based approaches, such as required for this project, have their limitations due to model simplifications, lack of data and unknown future developments. Some key points are outlined below.

With regard to the estimation of costs, a limitation of the VTT-TIAM model is the limited number of biomass cost steps that can be included. Since VTT-TIAM is a linear optimisation model, it simply chooses the cheapest biomass until the potential is reached, which can lead to an overestimation of a particular biomass source, whilst other sources are not selected, because the average cost is too high.

It is important to stress that the estimation of costs associated with the scenarios developed in this project inevitably involves considerable uncertainties, as for any such economic modelling exercise. Section 3.6 has discussed some these issues, particularly with regard to limited and uncertain data on the costs associated with future supplies of biomass, and has described a number of the assumptions made about these costs. The discussion in Section 3.6 also describes the efforts made in Task 2 to ensure that the cost estimates referred to in the modelling of bioenergy chains were not underestimated.

Most likely, the biggest source of uncertainty in the cost estimates involved in the calculation of results considered below is related to shifts in the use of wood co-produced for material wood products and concomitant changes in the consumption of counterfactuals.

As discussed in Sections 4.8.3 and explored as part of the assessment of final project results in Section 6, some results were produced for the scenarios developed in this project, which explored the potential for additional supporting measures aimed at avoiding or mitigating high GHG emissions associated with the supply and consumption of forest bioenergy sources. It is important to note that it was not possible as part of this project to assess the costs likely to be associated with such additional measures. However, the assessment of cost performance in this project, as described in Section 6.9, was based on results which did not allow for the potential contributions to GHG emissions reductions due to any such additional supporting measures. Hence, the calculations were consistent for all scenarios and the results as presented should be comparable.

The scenarios developed using the VTT-TIAM model represent competition between energy sources, but competition for the use of wood in the energy sector and other wood consuming sectors is not represented dynamically in VTT-TIAM. Instead, competition between these sectors is represented explicitly in the input assumptions to VTT-TIAM for each scenario, by referring to results for different EFSOS II scenarios (see Section 3.5.2 and Appendix 3). Whilst this approach was adopted in Task 2, interactions between the energy and other wood using sectors were further explored as part of a sensitivity analysis carried out in Task 3, involving application of the CARBINE model (see Section 4).

In undertaking the initial construction of each scenario, particularly when referring to targets for GHG emissions reductions, it was assumed that contributions to GHG emissions from biogenic carbon due to use of bioenergy were zero. Obviously, this assumption does not hold generally and, indeed, may strictly only apply rarely. Whilst contributions to emissions due to biogenic carbon of bioenergy are omitted in the analysis of Task 2, they are fully assessed for each scenario in Task 3. The overall assessment of carbon impacts due to biomass consumption for energy should thus be comprehensive. However, it is important to recognise that, because biogenic carbon emissions are assessed subsequently to the development of scenarios in Task 2, in practice, the GHG emissions reductions targets specified for each scenario in VTT-TIAM are unlikely to be met. Whilst this does not invalidate the scenarios or the subsequent assessment of GHG emissions (indeed, it is precisely the purpose of this project to identify and understand such impacts), ideally, the original VTT-TIAM scenarios should be re-run after the calculation of the additional biogenic carbon emissions in Task 3. However, such iterative steps to refine the scenarios were beyond the scope of this project.

In this project, considerable efforts have been made to ensure transparency in the calculation of the final results, including any underlying assumptions and data sources. In cases where complex models have been applied and transparency has been difficult to demonstrate, supporting examples of model calculations have been provided for simple scenarios, to enable the workings of models and their responses to be understandable. For example, worked examples of calculations and results for the MITERRA-Europe model and for the CARBINE model have been provided, respectively, in Appendix 7 and Appendix 8. However, this has not been entirely possible with regard to the calculations and production of results by the VTT-TIAM model. Some assurance may be offered regarding the accuracy of results produced by the VTT-TIAM model, from the fact that its outputs proved to be very consistent with the results of the PRIMES 2013 scenarios for future energy use in the EU, to which the model was only partially calibrated.

6.11.4. There are difficulties in determining the 'most likely' responses in forest management and wood use

As discussed extensively in the Task 1 report for this project, and in this final project report, specific outcomes for the GHG emissions associated with forest bioenergy use are strongly dependent on the types of forest bioenergy source, and the specific approaches taken to forest management and wood use as part of increasing the supply of forest bioenergy. Examples of the types of factor that can influence outcomes for GHG emissions are summarised in Section 7.2.5 as part of the conclusions of this report. However, it is very difficult to determine how forest management and patterns of wood use are likely to change in practice, as part of activities to increase the supply of forest bioenergy. In the assessment undertaken in this project, as described in Section 4.8.3, this has been addressed by exploring the sensitivity of GHG emissions associated with forest bioenergy to specific approaches to forest management and wood use.

Ideally, a comprehensive, multi-factorial sensitivity analysis with regard to forest management and wood use options would have been very valuable, but it was not possible within the scope of this project to model all possible cases of such approaches. Hence, two contrasting approaches were defined, referred to as the 'Precautionary' approach and the 'Synergistic' approach. As with the definition of the six scenarios developed in this project, these approaches are not intended to be a prediction of future changes to forest management and wood use. Rather, the approaches as defined represent two sets of contrasting actions, which might be adopted as part of taking forward policies towards bioenergy in the EU. In this context, a prediction of a most likely outcome is of less interest, compared with assessments for different possible scenarios, as considered in this project. It may also be noted that the essential purpose of the design of the 'Precautionary' approach was to represent a plausible set of changes in forest management and wood use to supply increased quantities of forest bioenergy in the EU. This was determined largely on the basis of expert judgement, but was undertaken systematically, by referring to the possible options for approaches to forest management and the utilisation of harvested wood that might be involved in forest bioenergy supply, as represented in the decision tree in Figures 2.1a to 2.1d (see Section 2.4).

The definitions of the 'Precautionary' and 'Synergistic' approaches to forest management and wood use included contrasting assumptions about future afforestation activities, notably in the EU27 region. For the 'Precautionary' approach, assumptions about afforestation were unchanged from the baseline. Under the 'Synergistic' approach, for the EU27 region, it was assumed that measures could be taken to enhance afforestation rates from 2016 onwards. This enhanced rate of afforestation was taken as three times the rate of afforestation observed in the year 2008. This rate of afforestation was assumed to be constant from 2016 onwards. However, to avoid risks of iLUC, the total afforested area was capped for each EU27 Member State, at 80% of the area of land available for afforestation, as estimated in Task 2 (see Section 4.7.1).

Consequently, for the 'Synergistic' approach, there is a significant spike in the rate of afforestation between 2016 and 2018 reflecting the assumption of a boost in afforestation activities from 2016, but constrained in the case of a number of Member States by the availability of land. The spike in the rate of afforestation is a distinctly theoretical scenario. However, it is suggested that this represents a maximum level for possible future afforestation activities. In conjunction with the conservative assumptions made about afforestation rates for the 'Precautionary' approach, the two scenarios may be taken to represent the range in possibilities for future afforestation activities in the EU27 region. Such an approach is appropriate for the sensitivity analysis with respect to forest management activities begin carried out here.

It must be noted that, in practice, there may be technical, economic and logistical constraints that would prevent a pronounced boost in afforestation rates over a short period, as represented for the EU27 region under the 'Synergistic' approach. In this context, some inertia in the forest sector must be recognised, reflecting the long-term planning needed over the timescales of forest rotations and the investments required to build up infrastructure for forest operations. On the other hand, the peak afforestation rate under the 'Synergistic' approach represents only a tripling of what are already quite modest afforestation rates reported for 2010 by most Member States.

It may also be noted that some transformation of land from non-forest cover to forest cover takes place naturally in the EU (as well as elsewhere), for example, when agricultural land is abandoned and then recolonised by regenerating trees. The inclusion of such forest regeneration in the scenarios considered for this project may be open to question. However, as already noted, the rates for afforestation referred to in this project have been formally reported by countries under the UNFCCC, as explicitly representing afforestation activities. These data may have limitations and associated uncertainties, but nevertheless represent the best information currently available.

It should be stressed that different results would be obtained for the scenarios developed in this project, if different assumptions were made about the specific sources of agricultural and forest biomass involved in the increased supply of bioenergy, and about the approaches taken to the management of agricultural and forest areas.

6.11.5. The scenarios only represent cases in which iLUC can be avoided

Indirect land-use change (iLUC) is a contentious but important potential cause of biogenic carbon emissions associated with changes to agricultural land use and management to increase supplies of bioenergy. The possibilities for the occurrence of iLUC, and its potential impacts, had to be addressed in developing and modelling the biomass and counterfactual scenarios considered in this project. As should be apparent from the preceding discussion, a precautionary principle was adopted, which involved constraining the extent of changes in agricultural land use and management represented in the biomass scenarios, to ensure that significant risks of iLUC should not arise. It follows that all the scenarios developed and assessed in this project represent cases in which iLUC can be avoided. Consequently, scenarios in which land-use change involved in the provision of increased levels of bioenergy have not been represented in this project.

6.11.6. There are inevitable uncertainties in consequential LCA studies

By nature, the results of consequential LCA studies, such as undertaken in this project, can involve significant uncertainties in underlying assumptions. The development and assessment of the scenarios considered in this project has necessarily involved a very great number of assumptions. The final project results, such as the estimated total annual GHG emissions associated with the various scenarios, are very sensitive to many of these assumptions. Notable examples have already been discussed in Sections 6.12.1, 6.12.3, 6.12.4 and 6.12.5.

In general, assumptions about changes in land use and in patterns of biomass use, associated with increased consumption of bioenergy, have a critical influence on the final results. Equally important are the related assumptions made about counterfactuals.

In the Task 1 report for this project, it was highlighted that the outcomes of GHG assessment of forest bioenergy are very sensitive to the counterfactual scenario for land use. The development of forest carbon stocks in the counterfactual land-use scenario, which considers the case in which increased consumption of forest bioenergy does not occur, requires assumptions to be made which can be highly uncertain. The projected development of forest carbon stocks under the counterfactual scenario will depend on the assumed forest management, the potential of the growing stock forming forest areas (tree species, age distribution, climatic conditions, soil quality, nutrient regime etc.), and on the likelihood of natural disturbances.

Similarly, outcomes are very sensitive to the counterfactual scenario for energy systems, which also involve assumptions which may be very uncertain, e.g. because of unforeseen market-mediated effects or future policy developments.

Uncertainties in counterfactual scenarios are inherent due to the fact that the counterfactual scenario is, by definition, a path that characteristically is not followed. It is thus never possible to verify what would have actually happened. Long time horizons related to forest carbon cycles and lifetimes of energy systems increase the inherent uncertainty.

Despite the preceding cautionary discussion, it may be noted that even after allowing for uncertainties, key outcomes of the assessment made in this project are unchanged (see for example Section 6.8). It should also be noted that major sources of uncertainties, in the form of assumed wood co-products, their counterfactuals and options for end-of-life disposal have been taken into account through evaluation of extreme ranges of results, as opposed to subsequent averages, in the workbook, “EC BCI Results v40.xlsx”.

6.11.7. There are some limitations in GHG emissions factors referred to in LCA calculations

LCA studies of GHG emissions rely on GHG emissions factors for their calculations. In this project, this has been the case particularly for the estimation of indirect GHG emissions as part of the assessment of the GHG emissions impacts of the scenarios developed in this project. The calculation of indirect GHG emissions and the application of GHG emissions factors have been described thoroughly in Section 5. Ideally, GHG emissions factors should vary with time, reflecting developments in the use of energy sources, other resources and associated technologies. Section 5.2 describes the general approach taken, but also noted that, in many cases, emissions factors were available for 2010, 2020 and 2030. In order to simulate estimated total GHG emissions for every year between 2010 and 2030 from these different outputs, formulae for simple linear interpolation were incorporated, as necessary, in the "EC BCI Results v40.xlsx" workbook for preparing final results. In the case of emissions factors between 2030 and 2050, it was assumed that these remained constant with respect to their 2030 values. This assumption is likely to overstate GHG emissions between 2030 and 2050 due to expected but currently unknown improvements in production and manufacturing technologies during this period. However, it should be noted that, in general, the contributions from these emissions factors are small compared with more prominent sources of GHG emissions, especially CO_2 emissions from biogenic carbon associated with net carbon stock changes in forests.

6.11.8. This assessment is restricted principally to the consideration of GHG emissions

Essentially, the investigation undertaken in this project has consisted of an assessment of the potential impacts on total annual GHG emissions, for a defined set of scenarios describing possible future developments in EU policy on energy, especially bioenergy. However, the potential impacts on GHG emissions represent just one possible type of impact that such policies may have. Ideally, a more comprehensive assessment is desirable which would also consider impacts on (for example):

- The nutrient status and water-holding capacity of agricultural and forest land, potential erosion of agricultural soils
- The stability of forest sites (e.g. with respect to wind risk)
- The eutrophication of surrounding watercourses and lakes
- The biodiversity of agricultural land areas and forest stands and the wider surrounding landscape, and
- Economic and social factors.

Ideally, this sort of comprehensive sustainability assessment of specified levels bioenergy supply from agricultural and forest biomass sources is very desirable. However, such a study would require a large body of supporting data, which in many cases, most likely, would not be available. A comprehensive study of all possible impacts would also involve a much more significant set of supporting assumptions, which would be even more challenging to define and properly document for the purposes of transparency.

Whilst the LCAs of GHG emissions undertaken for this project are narrow, in that wider environmental and social impacts are not considered, this should not invalidate the final results obtained for total annual GHG emissions and associated detailed analysis and interpretation. Apart from the fact that the evaluation of GHG emissions was the intended focus of this project, it should be recalled that the management and mitigation of GHG emissions is a *sine qua non* requirement for current policy formulation. Additionally, it is more appropriate for the site-specific nature of many other environmental and social impacts of bioenergy and other energy developments to be addressed by means of case-by-case assessments.

6.11.9. The final project results cannot be simply interpreted to determine the implications of the modelled scenarios, in terms of the capacity of EU Member States to meet EU domestic and international commitments for GHG emissions reductions

In Section 6.4, an explanation is provided of how this project has been designed to assess, comprehensively, impacts in terms of GHG emissions arising from increased consumption of biomass for energy in the EU. This is the approach required when undertaking an assessment of the impacts of a strategic policy or business decision, as determined by the conventions of consequential LCA (see Section 4 of the Task 1 report for this project). According to the conventions of LCA, the system boundary adopted for estimating emissions needs to encompass all of the parts of the system (and associated activities and processes) relevant to addressing the research question that has been stated. Owing to the nature of research questions associated with consequential LCA studies (such as in the case of this project), systems boundaries in consequential LCA frequently enclose a very large part of the world.

The system boundary adopted in this project flows from the research question or goal of the LCA study, which has been stated in the project purpose in Section 1.2.2 of this report. The LCA goal is stated as:

"to quantify the ***global*** *emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources resulting from implementation of possible EU policies represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050".*

The discussion of the project purpose in Section 1.2.2 notes that the consideration of possible policies for future energy consumption within the EU forms the starting point for the LCA. However, to assess the stated goal, it is necessary to account for subsequent prominent GHG emissions both within the EU and outside the EU due to the provision of imports of energy, including bioenergy, over a given period of time. Additionally, it is necessary to capture the changes in GHG emissions due to bioenergy displacing non-biomass energy and, where appropriate, non-energy products, referred to generally as 'counterfactuals'. This approach leads naturally to the requirement to consider the range of sources of GHG emissions identified and listed earlier in this section. An important point to note about such a comprehensive assessment is that it covers GHG emissions that are *external to, as well as included in*, national GHG inventories reported by EU Member States, or currently accounted for by EU Member States under the Kyoto Protocol.

It follows that the assessment undertaken in this project is very thorough, going broader than considering just the impacts of potential bioenergy consumption on GHG emissions that would need to be reported in emissions inventories or would need to be accounted for by EU Member States. However, an important consequence is that the final project results cannot be directly interpreted to understand the potential implications of the modelled scenarios for bioenergy consumption, in terms of the capacity of EU Member States to meet commitments for GHG emissions reductions, according to internationally-agreed conventions and accounting rules. In principle, the results of this project could be analysed further in order to assess such impacts, but such analysis was outside the scope of this current project.

7. Key conclusions and implications for bioenergy use

This project has undertaken a quantitative assessment of the impacts on GHG emissions associated with six scenarios for the supply and consumption of biomass for energy within the EU region. The six scenarios were designed to represent a range of possibilities for the future development of bioenergy use within the EU, in response to existing and possible future policies. One *reference scenario*, consistent with existing policies in the EU and without additional GHG and renewable energy targets after 2020 was developed, along with five *decarbonisation scenarios*, which represented different options for levels and sources of domestic and imported biomass use for electricity and heat generation in the EU for 2030 and 2050.

The **Reference Scenario A** represents the case where *existing policy targets* for renewable energy consumption and reductions in GHG emissions, set for 2020, should be met, but no further explicit policies or measures are taken to go further than the 2020 targets, either in terms of renewable energy consumption (including bioenergy consumption), or in terms of reductions in GHG emissions.

Four of the decarbonisation scenarios, **'Carry on' Scenarios (B, C1, C2 and C3)** represent cases in which policies and measures with regard to renewable energy consumption and reductions in GHG emissions go further than the existing 2020 targets, by setting more ambitious targets for 2030. The individual 'Carry on' Scenarios represent different options for increased levels of consumption of bioenergy beyond the 2020 targets, and particular sources of bioenergy supply:

- B ('Carry on/unconstrained use') – highest use of biomass for energy, from all sources, i.e. with limited constraints on the types of sources consumed
- C1 ('Carry on/imported wood') – emphasises the consumption of imported forest bioenergy
- C2 ('Carry on/domestic crops') – emphasises the consumption of bioenergy from energy crops and agricultural biomass grown in the EU region
- C3 ('Carry on/domestic wood') – emphasises the consumption of forest bioenergy, supplied from forests in the EU region.

A further decarbonisation scenario, **Scenario D ('Back off')**, represents a situation involving the same ambitious targets for 2030 as in the 'Carry on' Scenarios. However, the consumption of bioenergy as a renewable energy source for meeting these targets is de-prioritised post 2020. Consequently, targets post 2020 have to be met by consuming other sources of energy and/or achieving greater energy efficiency.

In this section, key conclusions are summarised with regard to the main project findings on:

- Potential impacts in terms of GHG emissions associated with the supply of biomass from various sources, for use as energy in the EU region, as assessed using the scenarios developed in this project (see Section 7.1)
- Possible future contributions to energy use in the EU region due to bioenergy sources, as assessed based on the scenarios developed in this project (see Section 7.2)

- The possibilities for refinement of the scenarios considered in this project (see Section 7.3).

Based on the conclusions in Sections 7.1 to 7.3, some implications for bioenergy use are discussed in Section 7.4. Some recommendations for further research are given in Section 7.5.

7.1. Conclusions on impacts on total GHG emissions

The ultimate aim of this project has been to produce final quantitative results that consist of estimated total annual GHG emissions for the EU27 region under these six different scenarios for the period between 2010 and 2050. The derivation of these estimated GHG emissions was achieved using the outputs produced in Tasks 2 to 4 of this project from the VTT-TIAM model, the CARBINE model, the MITERRA-Europe model and pathway workbooks. All these outputs were brought together in a consistent and interrelated manner to obtain estimates of total GHG emissions for the EU27 region under each scenario over the period from 2010 to 2050.

Sections 3, 4 and 5 of this report have described the work done under Tasks 2 to 4 of this project to:

- Define and elaborate, quantitatively, scenarios for bioenergy consumption and supply in the EU up to 2050 (Task 2, Section 3)
- Estimate the impacts of increased bioenergy consumption in the EU on the management of crops and forests, on the supply of biomass for energy and non-energy uses, and on land-based carbon dynamics, and CO_2 emissions associated with biogenic carbon of bioenergy (Task 3, Section 4)
- Estimate the (indirect) GHG emissions associated with the processes of bioenergy production, transport, processing, conversion and use of bioenergy in the EU, including associated impacts on consumption of biomass for non-energy uses (Task 4, Section 5).

The integration and presentation of the outputs of Tasks 2 to 4 to produce the final project results has been described in Section 6, which also provides an assessment of the final results.

The quantitative assessment of GHG emissions associated with the consumption of bioenergy in the EU has involved estimating:

- Changes in carbon sequestration (increases or decreases over time) on agricultural land and in forest areas, due to the production of additional bioenergy
- Biogenic carbon emissions and indirect GHG emissions due to the combustion of the bioenergy
- Emissions avoided due to displacement of counterfactual energy sources
- Changes in GHG emissions (increases or decreases) due to the diversion of certain agricultural biomass sources from non-energy uses to use as bioenergy
- Changes in GHG emissions (increases or decreases) due to the diversion of wood from use for material wood products, to use instead as forest bioenergy, including impacts on GHG emissions occurring when materials are disposed of at end of life

- Changes in GHG emissions (increases or decreases) due to any co-production of additional material wood products in conjunction with the supply of the additional forest bioenergy, including the displacement of counterfactual materials and impacts on GHG emissions occurring when materials are disposed of at end of life.

This holistic approach to estimating GHG emissions follows from the system boundary adopted for LCA calculations in this project. In turn, as explained in Section 6.4, the system boundary flows from the research question or goal of the LCA study, which has been stated in the project purpose in Section 1.2.2 of this report. The LCA goal is stated as:

*"to quantify the **global** emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources resulting from implementation of possible EU policies represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050".*

The final project results, constituting the assessment of GHG emissions associated with the consumption of bioenergy in the EU has been discussed in detail in Section 6. The Key conclusions are summarised below.

7.1.1. All scenarios achieve significant reductions in total annual GHG emissions, including those scenarios involving increased bioenergy consumption

An assessment of the main results for all six scenarios developed in this project, based on consideration of trajectories of total annual GHG emissions over time, indicates that the trends for all trajectories are consistently and significantly downwards, i.e. total annual GHG emissions are reduced over time.

The suggestion is that all of the scenarios considered in this project representing different possible EU policies with regard to bioenergy, i.e. involving continued or increased bioenergy consumption in some form, or a backing off from consumption of bioenergy, can achieve reductions in GHG emissions.

These observations lead to the conclusion that, if bioenergy contributes towards future (renewable) energy supply in the EU region, it is also possible to achieve overall reductions in total annual GHG emissions.

The projected changes in total annual GHG emissions, as modelled in this project, occur as a result of a combination of changes in energy use over time in the EU27 region. As a consequence, the contribution made specifically by bioenergy to net changes in GHG emissions over time is difficult to discern from overall results for total annual GHG emissions. This has been clarified by further detailed analysis.

Overall, under the high-bioenergy 'Carry on' Scenarios (compared with Scenario A), the net impact of bioenergy is a significant contribution towards the overall net GHG emissions savings achieved in 2030, alongside contributions due to other sources (CCS, energy efficiency, nuclear and other renewable energy sources). In contrast, under the 'Back off' Scenario D, the reduced consumption of bioenergy in general leads to a net increase in GHG emissions in 2030.

The contributions made by bioenergy towards net GHG emissions savings in 2030 are generally beneficial. However, the detailed contributions are variable, depending on the scenario. The contribution of bioenergy towards GHG emissions savings is higher for scenarios emphasising bioenergy supply from domestic sources and lower for scenarios emphasising consumption of imported forest bioenergy and/or the relatively unconstrained use of bioenergy sources.

Further conclusions arising from the analysis of the contributions of bioenergy sources to the GHG emissions estimated for the scenarios developed in this project are discussed in Sections 7.1.5 to 7.1.7.

See Sections 6.5 and 6.9 (particularly Section 6.9.3) for supporting discussion of these points.

7.1.2. Greater reductions in total annual GHG emissions can be achieved by decarbonisation scenarios involving either increased bioenergy consumption or through decreased bioenergy consumption, compared to Reference Scenario A

The reductions in total annual GHG emissions for the various decarbonisation scenarios, i.e. the 'Carry on' Scenarios, and Scenario D ('Back off'), are all consistently and significantly deeper, compared with Reference Scenario A. This indicates that all of the scenarios considered in this project representing different possible EU policies with regard to bioenergy, i.e. involving continued or increased bioenergy consumption in some form, or a backing off from consumption of bioenergy, can achieve reductions in GHG emissions. In the context of future development of EU energy policy, the 'bioenergy option' may be viewed as neither a 'show-stopper' nor a 'must-have' from the simple perspective of total annual GHG emissions alone.

By nature, the results of consequential LCA studies, such as undertaken in this project, can involve significant uncertainties. However, even after allowing for uncertainties, the assessment of this project indicates that estimated total annual GHG emissions in 2030 and 2050 are evidently lower for all the various 'Carry on' Scenarios and for the 'Back off' Scenario D, compared with the Reference Scenario A.

See Sections 6.5, 6.6 and 6.7 for supporting discussion of these points.

7.1.3. A ranking is apparent in the outcomes achieved by the decarbonisation scenarios, in terms of reductions in total annual GHG emissions

The results indicate an apparent ranking in the outcomes achieved by the decarbonisation scenarios, in terms of reductions in total annual GHG emissions, relative to the Reference Scenario A:

- A decarbonisation scenario involving de-prioritisation of bioenergy consumption in the EU post 2020 (Scenario D, 'Back off') achieves the biggest improvement in total annual GHG emissions reductions (3.4 GtCO_2-eq. yr^{-1} by 2050)
- Decarbonisation scenarios emphasising the increased supply of bioenergy from domestic agricultural or forest bioenergy sources post 2020 (Scenario C2, 'Carry on/domestic crops' and Scenario C3, 'Carry on/domestic wood') achieve marginally smaller improvements in total annual GHG emissions reductions, compared with the 'Back off' Scenario D, although the outcomes for Scenarios C2, C3 and D in terms of the GHG emissions reductions achieved by 2050 are quite close (respectively 3.1, 3.1 and 3.4 GtCO_2-eq. yr^{-1} between 2010 and 2050).
- Decarbonisation scenarios emphasising the increased supply of forest bioenergy imported from outside the EU post 2020 (Scenario B, 'Carry on/unconstrained use' and Scenario C1, Carry on/imported wood') achieve the smallest improvements in total annual GHG emissions reductions. However, the outcomes for Scenarios B, C1, C2 and C3, in terms of GHG emissions reductions achieved by 2050, are quite close (respectively 2.7, 2.7, 3.1 and 3.1 GtCO_2-eq. yr^{-1} between 2010 and 2050).

The consideration of uncertainties in estimates does not alter the ranking in the results for total annual GHG emissions reductions. At the same time, quite large uncertainties in results may be relevant when considering the closeness in outcomes, in terms of GHG emissions reductions, for some of the scenarios, thereby warranting caution in inferring conclusive distinctions. In general, the impacts of increasing or decreasing consumption of bioenergy on the potential for achieving reductions in total annual GHG emissions in 2030, as represented in the scenarios developed in this project, are quite marginal, with the notable exception of a scenario in which the (relatively unconstrained) use of imported forest bioenergy is emphasised (Scenario C1).

See Sections 6.5.2, 6.6, 6.7 and 6.9.4 for supporting discussion of these points.

7.1.4. Future energy demands and GHG emissions reductions can be met without prioritising bioenergy, but with high associated costs and certain logistical challenges

This project has included an assessment of the cost performance of the decarbonisation scenarios considered in this project, relative to the Reference Scenario A, with results expressed in terms of Euros per tonne of GHG emissions abated (i.e. in units of €/tCO_2-eq.), and as a share of GDP (i.e. in *% of GDP).*

This assessment identified that the 'Back off' Scenario D stands out as significantly more expensive, in terms of cost performance, compared with all of the 'Carry on' Scenarios:

- By between around 315% (compared with Scenario C3) and 350% (compared with Scenarios B and C2) in 2030, falling to between around 175% (compared with Scenarios C2 and C3) and 180% (compared with Scenario C1) in 2050, **based on the marginal energy system cost**
- By between around 110% (compared with Scenario B) and 140% (compared with Scenario C3) in 2030, rising to between around 160% (compared with Scenario B) and 225% (compared with Scenario C3) in 2050, **based on the marginal carbon price**

- By between around 145% (compared with Scenario C1) and 190% (compared with Scenario C2), **based on the average GHG reduction cost over the period 2010 to 2050.**

Amongst the various 'Carry on' Scenarios, Scenarios C2 ('Carry on/domestic crops') and C3 ('Carry on/domestic wood'), i.e. the high-bioenergy scenarios that put less emphasis on imported biomass supply, appear to give the most favourable results in terms of overall cost performance and levels of reductions in total annual GHG emissions.

It follows that future energy demands can be met without prioritising bioenergy, but most likely at much higher cost.

It should be stressed that the poorer cost performance of Scenario D, in comparison with the 'Carry on' Scenarios, does not imply that the other renewable energy sources used in place of bioenergy in Scenario D must cost significantly more than bioenergy sources. Rather, the higher costs of Scenario D are associated generally with the challenges involved in meeting the targets set for levels of renewable energy consumption and GHG emissions reductions, whilst also de-prioritising the consumption of bioenergy. In this respect, the results for Scenario D indicate that the available lower-cost options are not sufficient to meet the targets set for renewable energy supply and GHG emissions reductions, if bioenergy is not also available as an option, therefore higher-cost options also need to be included as part of actions taken. Scenario D also involves some logistical challenges, with implications for costs, e.g. more concerted efforts towards energy efficiency in the EU region across all sectors, significant expansion of the use of nuclear power, and increased importation of natural gas, nuclear fuels and electricity into the EU region from elsewhere.

When assessing and comparing the scenarios developed in this project, the measures of cost performance discussed in this section can be regarded as a complement to the results for the reductions in total annual GHG emissions achieved by the scenarios, as described in Sections 7.1.1 to 7.1.3. However, as stressed repeatedly in earlier discussions, it is important to note that the actual contribution made by bioenergy to net changes in GHG emissions over time is not completely apparent from results based on total annual GHG emissions. This has been clarified by further detailed analysis, and relevant conclusions arising from this analysis are discussed in Sections 7.1.5 to 7.1.7.

See Section 6.8 for supporting discussion of these points.

7.1.5. Differences between outcomes for decarbonisation scenarios, in terms of the GHG emissions reductions achieved, reflect underlying variations in the detailed contributions made by specific sources of bioenergy.

The results for total annual GHG emissions reductions for the various decarbonisation scenarios reflect underlying detailed contributions made by specific sources of bioenergy. As already implied by the assessment in Section 7.1.3:

- The smaller GHG emissions reductions achieved by Scenarios B ('Carry on/unconstrained use') and C1 ('Carry on/imported wood'), compared with the other

decarbonisation scenarios, derive principally from the emphasis on imported forest bioenergy sources which involve relatively high GHG emissions, particularly biogenic carbon emissions.
- The relatively high GHG emissions reductions associated with Scenario C2 ('Carry on/domestic crops') derive principally from the low GHG emissions, including biogenic carbon emissions, due to the emphasis on use of agricultural biomass for energy.
- The relatively high GHG emissions reductions associated with Scenario C3 ('Carry on/domestic wood') derive principally from the lower reliance on imported forest bioenergy sources, which leads to smaller increases in GHG emissions from these sources. The greater emphasis on use of domestic forest bioenergy leads to increased GHG emissions from these sources, including biogenic carbon emissions, but the increases are smaller than those associated with imported forest bioenergy sources.
- The relatively high GHG emissions reductions associated with Scenario D ('Back off') derive principally from the avoidance of GHG emissions, including biogenic carbon emissions, due to the generally reduced consumption of bioenergy. Instead, there is increased use of other renewable energy sources, more concerted efforts towards energy efficiency in the EU region, significant expansion of the use of nuclear power, and increased importation of natural gas, nuclear fuels and electricity into the EU region from elsewhere.

Beyond this broad assessment, there are some potentially important variations in the GHG emissions of specific bioenergy sources, which also explain some of the distinctions between sources identified above.

For all scenarios, GHG emissions, including biogenic carbon emissions, associated with increased use of agricultural sources of bioenergy (produced within the EU27 region), associated with increased use are consistently low, compared with fossil energy sources. However, significant variations in GHG emissions for specific agricultural biomass sources should be noted. In particular, the establishment of energy crops in the EU, as represented in the scenarios, generally leads to carbon sequestration. Conversely, the removal of agricultural residues, notably straw, leads to increased biogenic carbon emissions.

For forest bioenergy sources, GHG emissions, including biogenic carbon emissions, associated with increased use vary considerably in magnitude, and also over time (see, in particular, Section 4.10.6). The results for the biogenic carbon emissions of different forest bioenergy sources are very variable, ranging from approximately 1.5 times that of coal, to moderately negative, and even significantly negative in conjunction with additional supporting complementary actions (see Section 7.1.7). Specific outcomes for GHG emissions are strongly dependent on the types of forest bioenergy source and their geographical origins (e.g. produced domestically within the EU27 region, or imported from Canada, the USA, and the CIS region or possibly from dedicated biomass plantations in Brazil). However, these results are closely related to differences in important associated assumptions about the growth rates of the forests involved, forest management approaches, subsequent biogenic carbon emissions, types of feedstock for forest bioenergy, interactions with material wood products and their associated counterfactuals, and end-of-life disposal pathways for material wood products.

It is important to appreciate that there is an intimate linkage between the outcomes reported as the main results of this project and the underlying assumptions highlighted above.

See Sections 2, 4.8.4, 4.9.4, 4.10.6, 6.6, 6.7 and 6.9.4 for supporting discussion of these points.

7.1.6. Levels of bioenergy use under all scenarios in 2030 are consistent with sustainable-yield supply, but levels of forest bioenergy supply in high-bioenergy scenarios in later years are challenging, with high associated GHG emissions

For the scenarios assessed, levels of agricultural biomass production for energy use within the EU27 region are consistent with the avoidance of significant risks of iLUC. Additionally, levels of forest biomass supply for use as energy, produced domestically within the EU27 region or supplied from elsewhere, are assessed as consistent with sustainable yield, depending on the levels of demand for forest biomass in other sectors and geographical regions. However, pronounced increases in the levels of forest bioenergy consumption (and therefore supply) from some point after 2030 up to 2050, as represented in the high-bioenergy scenarios developed in this project, lead to net increases in total GHG emissions associated with the supply of forest bioenergy, for most sources. This is particularly significant for scenarios that emphasise the importation of forest bioenergy into the EU. It follows that any targets for future levels and rates of increase in forest bioenergy supply need to be set with care, with particular regard to time-dependent impacts on biogenic carbon emissions as well as potentials for sustainable-yield supply (see Section 7.2.3).

In order to reduce risks of net increases in GHG emissions, the increases in levels of consumption of forest bioenergy, notably in the form of imports, after 2030, suggested by the high-bioenergy scenarios developed in this project, should be avoided, unless additional supporting measures can be applied to ensure that increased production of forest bioenergy leads to overall positive impacts on GHG emissions (see Section 7.1.7).

See Sections 6.6, 6.7 and 6.9.4 for supporting discussion of these points.

7.1.7. Risks of high GHG emissions associated with forest bioenergy use can be significantly mitigated by adopting additional supporting positive approaches to forest management and wood use

If additional measures that support the use of forest bioenergy with low associated GHG emissions can be explicitly linked to activities aimed at increasing the production of forest bioenergy, then substantive reductions in total GHG emissions can be achieved. Relevant measures have been discussed at various points in this report, and in the Task 1 report for this project, and these discussions are synthesised and summarised in Sections 7.4.3 and 7.4.4, and in particular Section 7.4.5.

See Sections 2.3.13, 2.3.14, 4.10.6, 6.7.2, 6.7.3 and 6.9.4 for supporting discussion of these points.

7.1.8. The potential impacts of agricultural biomass use for energy on soil organic carbon and nutrient status require careful management

At the scale of individual farm fields, the removal of straw for bioenergy might decrease the soil organic carbon level, which might potentially lead to a decrease in crop yield, e.g. due to a lower water holding capacity and lower nutrient retention. Nevertheless, in regions with high crop production, carbon inputs through roots and stubbles can be sufficient to maintain soil carbon levels while removing all straw for bioenergy. In addition, improved soil management, e.g. the use of cover crops or reduced tillage, might reduce the negative soil organic carbon balance due to straw removal.

The removal of agricultural crop residues for use as bioenergy will generally have impacts on the nutrient regime of affected agricultural land areas. In many situations, it will be necessary to remediate any nutrient deficiencies arising from such practice (e.g. through the application of fertiliser). The GHG emissions associated with possible remedial activities (e.g. the application of additional fertiliser) have been assessed. It should also be noted that the impact of removing crop residues on N_2O emissions (which are likely to be reduced) have also been assessed in this project.

In general, it may be concluded that, production of agricultural biomass to meet high-level targets for bioenergy would require careful interpretation and implementation at the regional and local scales.

See Sections 4.9.4 for supporting discussion of these points.

7.2. Conclusions on the potential contribution of bioenergy to energy use in the EU

7.2.1. Targets in 2030 for contributions made by renewable energy sources to energy use in the EU can be met with or without increasing the contribution from bioenergy

The Climate and Energy Policy Framework (European Council, 2014) specifies that "an EU target of at least 27% is set for the share of renewable energy consumed in the EU in 2030".

The assessment undertaken in this project suggests that the specified target for contributions to "energy consumed in the EU" (assuming this refers to final energy consumption), from renewable energy sources would be met under all scenarios considered in this project, with the exception of the Reference Scenario A. In other words, it is technically possible to meet the target with or without an increased contribution from bioenergy, compared with 2020 levels. It may be noted that the high-bioenergy scenarios typically involve higher contributions from bioenergy to final energy consumption of about 17% to 18%, and to TPES of about 14% to 15%.

With regard to the above conclusion, it is important to recall that the modelling of the scenarios developed in this project simulated the potential development of a range of possible renewable energy sources, not just bioenergy, and also represented measures aimed at improved energy conversion and efficiency. Under all the decarbonisation scenarios developed in this project, a target of 27% for the share of renewable energy sources consumed in the EU (expressed in terms of final energy consumption) is slightly exceeded (at 30%).

The modelling of scenarios for energy use in the EU, as undertaken in this project, involved disaggregating the bioenergy contribution to TPES into the four broad categories of biomass, bioliquids, biogas and biowaste.

If biomass were to be used to contribute towards the EU's 2030 target for consumption of renewable energy sources, then the contribution of primary biomass sources to TPES would need to be around 10% to 11%.

See Sections 3.7.1, 4.10.4, 6.9.1 and 6.9.2 for supporting discussion of these points.

7.2.2. Agricultural and forest biomass sources both make important contributions to biomass supply for energy

Under the scenarios considered in this project, domestically-produced agricultural and forest biomass, and imported forest biomass, all make important contributions to biomass supply for energy, although shares differ among the scenarios and over time. The relative contributions due to agricultural biomass and forest biomass for energy (domestically produced and imported), vary depending on the scenario, as would be expected from their definitions.

See Sections 3.7.2 and 3.7.3 for supporting discussion of these points.

7.2.3. Projected levels of forest bioenergy supply in 2050 under the high-bioenergy scenarios present risks to sustainable yield

Projected estimates for contributions made by bioenergy to TPES in 2050 are challenging from a practical standpoint. The assessment undertaken in this project suggests that the levels of forest bioenergy production represented in the scenarios by 2050 are likely to involve very significant risks to the sustainable-yield supply of wood from within the EU27 region, and also some risks for at least some regions outside the EU involved in the supply of forest biomass to the EU. This point has also been considered in Section 7.1.4, from the perspective of impacts on GHG emissions.

There is some evidence that the levels of forest bioenergy supply in some scenarios post 2030, and particularly after 2040, involving significantly increased forest bioenergy consumption, approach the limits of sustainable-yield supply, particularly in the EU region, but also with notable impacts in other regions, such as the USA. Further increases in total production above this level are likely to involve very significant risks to achieving wood supply in the EU27 region consistently with the principle of sustainable yield.

More generally, it may be noted that the scenario with the highest potential for consumption of bioenergy would involve a doubling of today's levels. Producing more biomass than this level for bioenergy in the EU within sustainable limits is not possible without large system changes.

In considering the preceding assessment, it should be noted that when estimating potential production from forests in the EU27 region, forest areas classified in National Forest Inventories as 'not available for wood production', or for management for protection, amenity or specific environmental objectives were excluded.

See Sections 4.8 and 4.10.4 for supporting discussion of these points.

7.3. Conclusions on refined high-bioenergy scenarios

The assessment of the 'Carry on' Scenarios developed in this project, and the conclusions reached in Sections 7.1 and 7.2, suggest scope for refined scenarios for energy consumption in the EU, involving relatively high bioenergy use, based on a number of building blocks:

- Building block 1 – Noting that the Climate and Energy Policy Framework specifies that "an EU target of at least 27% is set for the share of renewable energy consumed in the EU in 2030" (European Council, 2014), a refined scenario might involve setting a 2030 target for primary biomass sources to contribute about 11% to TPES in 2030, or about 160 Mtoe.
- Building block 2 – A 2030 target or limit for consumption of agricultural biomass for energy could be set within the range suggested for 2030 between roughly 75 Mtoe yr^{-1} and roughly 105 Mtoe yr^{-1}.
- Building block 3 – A 2030 target or limit for consumption of forest biomass for energy could be determined as the remainder required to meet an overall target for biomass consumption in the EU27 region. In order to meet a target contribution to TPES due to biomass of 11% to 12% (see Section 7.1.1), this suggests a level of supply of forest bioenergy between 55 to 85 Mtoe yr^{-1}.
- Building block 4 (option 1) – A balance should be found between the supply of forest bioenergy from domestic and imported sources. This might involve requiring consumers to limit the use of imported forest bioenergy sources to no more than (roughly) 20 Mtoe, or between 25% to 35% of total forest bioenergy consumption by energy content (depending on the target for the overall contribution of forest bioenergy), or conversely to ensure the use of domestic forest bioenergy sources up to at least 35 to 65 Mtoe (depending on the target for the overall contribution of forest bioenergy), or 65% to 75% of total forest bioenergy consumption, and the adoption of an 'effort sharing' principle.
- Building block 4 (option 2) – An alternative to setting a balance between the supply of forest bioenergy from imported and domestically-produced sources would be to further clarify whether there are significant variations in sources of imported forest bioenergy, in terms of low or high risks to GHG emissions. The outcome of such an analysis could be used to inform sustainability criteria attached to all sources of forest bioenergy,

regardless of their geographical origin, and could also inform the design of additional supporting measures as considered in Building block 6.

- Building block 5 – Post 2030, levels of biomass consumption for energy should not increase further. If a future assessment and strong evidence were to indicate, clearly, that higher levels of consumption can be achieved without incurring increases in GHG emissions and within the limits of sustainable-yield production, then the constraining of biomass consumption for energy to 2030 levels could be reviewed.
- Building block 6 – There is a strong case for explicitly linking the supply/consumption of bioenergy, particularly forest bioenergy, to supporting measures aimed at ensuring low associated GHG emissions.

The design of these building blocks has been informed by the assessment of the six scenarios developed in this project, taking into consideration:

- A requirement for agricultural biomass production for energy within the EU27 region not to incur significant risks of iLUC
- A requirement to produce forest biomass within the EU27 region for use as energy, without approaching the limits of sustainable-yield supply, whilst limiting negative impacts on the soil nutrient status of forest sites, and without causing significant diversion of wood supply from use for material wood products to use for energy
- A requirement to produce forest biomass in regions outside the EU region for use as energy within the EU region, without approaching the limits of sustainable-yield supply, whilst limiting negative impacts on the soil nutrient status of forest sites, and without causing significant diversion of wood supply from use for material wood products to use for energy
- An aim of ensuring the minimisation or mitigation of biogenic carbon emissions associated with the increased production and supply of forest biomass from all geographical regions, for consumption as energy within the EU region.

Refined scenarios such as defined above could be subjected to an assessment of GHG impacts, as undertaken for the agreed scenarios developed in this project.

See Section 6.10 for supporting discussion.

7.4. Implications for bioenergy use

7.4.1. Proceed, but with caution

There is a key question that needs to be addressed as part of outcome of this project:

According to the findings of the project, how should the use of bioenergy be regarded, as an option for contributing towards future energy use in the EU, whilst also achieving overall reductions in GHG emissions?

Based on this quantitative assessment, it is concluded that the use of bioenergy in the EU should proceed with caution.

It should be apparent that no single energy source will serve as a sole solution for meeting future energy requirements in the EU. In particular, like any other form of energy (including other renewable energy sources), the supply and consumption of biomass for energy has associated costs, issues and risks. The assessment of bioenergy consumption and supply in this project has focused on impacts on GHG emissions, with some consideration of costs. Based on the assessments made in this project, as described in Sections 2 to 6, and the conclusions drawn in Sections 7.1 to 7.3, it is suggested that bioenergy, if supplied and used appropriately, should be viewed, from a policy perspective, as a credible option for the supply of renewable energy, alongside other renewable energy sources. This inference follows from the detailed consideration of the quantitative assessment of the scenarios developed in this project, which show that:

- Bioenergy use can lead to emissions reductions, even when contributions due to biogenic carbon are included in the assessment, provided that suitable bioenergy sources and approaches to production are involved
- Scenarios that avoid significant reliance on bioenergy use can lead to bigger emissions reductions, although at significantly higher costs and involving some logistical challenges (e.g. more concerted efforts towards energy efficiency in the EU region across all sectors, and increased reliance on fossil and nuclear fuels and electricity imported into the EU region from elsewhere).

Whilst acknowledging the potential for a positive contribution by bioenergy to future energy use in the EU, it is also evident from the assessments made in this project that, if the supply and use of bioenergy is not managed carefully, then there are, potentially, substantive risks associated with the increased use of bioenergy, particularly forest bioenergy, in terms of net impacts on GHG emissions. This is particularly apparent in the assessments of scenarios involving a relatively high contribution due to forest bioenergy imported from other regions into the EU. However, fundamentally, comparison of these scenarios with those which emphasise reliance on domestic sources of bioenergy demonstrates the high dependence of outcomes, in terms of GHG emissions reductions, on specific assumptions about approaches to forest management and changes in patterns in the use of wood, involved in increasing the supply of forest bioenergy. The essential issue identified by the assessments of the various ‘Carry on’ Scenarios developed in this project is not so much related to the geographical region from which forest bioenergy is supplied, but a reflection of the assumptions made about changes in forest management and wood use associated with the supply of those sources.

The preceding position with regard to bioenergy, specifically forest bioenergy, has been echoed in a recent review article by Ter-Mikaelian *et al.* (2015), in which the authors recognise the potential for forest bioenergy to contribute towards energy supply with low associated GHG emissions, but also highlight that such outcomes are not guaranteed for all possible sources. The authors stress the need for accurate assessment of the ‘atmospheric effects’ of bioenergy and caution against avoiding false promises of instant benefits to climate change mitigation, in situations where this does not occur as a result of the use of certain types of bioenergy source. It is pertinent to note that, despite the existence of a large body of literature on forest bioenergy and associated GHG emissions, Ter-Mikaelian *et al.* (2015) highlight a number of examples illustrating that misconceptions about the potential benefits and/or risks associated with forest bioenergy continue to be widely held.

Similarly, based on the quantitative assessment presented in this final project report, it is suggested that the position ultimately arrived at does not signify either a 'stop' or 'go' signal for the future potential of bioenergy in contributing to energy use with low associated GHG emissions in the EU. Rather, the assessment suggests a signal of 'proceed, but with caution'. Given the many challenges and uncertainties surrounding future energy provision in the EU and globally, it seems reasonable to suppose that bioenergy is not unique as an energy source in requiring very careful consideration regarding approaches to its future deployment.

The assessment presented in this final project report has suggested several approaches to exercising caution and minimising risks associated with the future consumption of bioenergy within the EU region.

7.4.2. Bioenergy supply informed by the assessment of scenarios

The assessment of the final project results discussed in Section 6, in particular Section 6.10, has enabled the identification of a number of building blocks for refined scenarios suggesting overall levels of biomass consumption for energy, and a mix of bioenergy sources (e.g. agricultural and forest-based bioenergy, possibly a balance between domestically-produced and imported bioenergy sources), generally consistent with:

- Avoiding serious risks of iLUC (mainly with regard to agricultural biomass sources)
- Keeping levels of biomass supply within the scope of sustainable-yield capacity
- Avoiding excessive impacts on the carbon stocks of forests inside and outside the EU (trees, litter and soil), and their capacity for future carbon sequestration, due to biomass production and supply to the EU
- Avoiding negative impacts on the potential supplies of wood for the manufacture of material wood products.

7.4.3. A systematic approach to classifying bioenergy sources

Bioenergy sources are variable in terms of associated GHG emissions, but it is possible to identify systematic causes of this variability. This suggests the possibility of screening sources of bioenergy for high, moderate or low risk with regard to GHG emissions.

The qualitative assessment undertaken in Task 1 of this project has considered possible approaches to favouring the use of low-risk sources of bioenergy (particularly forest bioenergy), in terms of impacts on GHG emissions, whilst de-prioritising the use of high-risk sources. The adoption of a system for ranking different sources of bioenergy, in terms of their associated GHG emissions, has an intuitive appeal. However, for reasons discussed at length in the Task 1 report for this project, it is very difficult to devise a simple system for classifying bioenergy sources according to their risk. This is because, in general, it is impossible to relate risks related to GHG emissions in a simplistic way to different types of biomass feedstock, such as 'straw', 'forest harvest residues', 'small roundwood' etc. (see Section 2.3.11 of this report, and the full Task 1 report for more discussion).

In fact, an attempt was made in Task 1 to rank forest bioenergy sources in terms of risks related to GHG emissions (see Table 2.1, Section 2.3.10 in this final project report), and this table illustrates the problem. As is apparent from Table 2.1, the definition of a specific forest bioenergy source may need to be detailed, with a number of qualifying clauses, identifying:

- The types of forest management involved in forest bioenergy supply
- The counterfactual land uses/forest management
- The types of wood feedstock used for bioenergy
- The counterfactual uses for any harvested wood
- Whether the supply of forest biomass for energy involves the co-production of material wood products, or the diversion of wood from use for the manufacture of material wood products to use for energy
- A range of other possible factors, e.g. the growth rates of affected forest areas, potential impacts on the nutrient status and soil quality of affected sites.

The interplay amongst a range of factors potentially involved in determining the GHG emissions associated with supplies of forest bioenergy has been illustrated in Figure 3.8 in Section 3.17 of the Task 1 report for this project.

It follows that a complete table, giving a comprehensive, ranked list of types of bioenergy sources (limited to forest bioenergy or wider) would need to be very long. There would also need to be multiple entries for bioenergy sources, which, superficially, might look the same, but would actually involve subtle but important distinctions, leading to markedly different risks being attached to them, in terms of potential impacts on GHG emissions.

Given the difficulties surrounding any attempts to construct a ranked list of bioenergy sources, in terms of impacts on GHG emissions, an alternative approach has been explored in an elaboration of the findings of Task 1 of this project (see Section 2.4 of this final project report). Specifically, an attempt has been made to construct a provisional version of a decision tree (Figures 2.1a to 2.1d in Section 2.4), for assessing the quantities of forest bioenergy that are likely to be associated with negative to low, moderate or high risks of significant GHG emissions. An illustration of the application of this decision tree has been given in Appendix 1.

As stressed in Section 2.4 and emphasised in Section 4.10.6, further work may be needed on this decision tree; in particular, some further clarifications, amendments or elaborations may be needed in order for it to attract wide acceptance amongst stakeholders. It must also be acknowledged that the decision tree is quite large and has many possible options and branches. Nevertheless, the approach is systematic and the choices amongst forest bioenergy sources should be reasonably clear. At least in principle, an approach to screening sources of forest bioenergy for high or low risk with regard to GHG emissions based on a decision tree could represent one possible way of addressing any requirement to reduce risks of high GHG emissions associated with the use of bioenergy.

7.4.4. A systematic but flexible approach to quantitative assessment of bioenergy supply chains

As explained in Section 2.3.13, the qualitative assessment undertaken in Task 1 has also lead to the suggestion that one possible step towards managing risk associated with increased consumption of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects (perhaps on the scale of several tens of megawatts) in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. This would require *strategic assessment* of the GHG emissions impacts of commercial decisions involving major changes in activities that will lead to increased consumption of forest bioenergy, in principle similar to the assessment of policies.

Some relatively recent developments with regard to such methodologies should be noted, in particular, the Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, proposed by the US EPA (EPA, 2014). As part of future work, there may be merit in evaluating the EPA methodology alongside a specific implementation of the more flexibly-defined approach suggested in the Task 1 report, perhaps through consideration of suitable case studies, either actual or hypothetical.

7.4.5. Linkages between bioenergy supply and supporting positive approaches to forest management and wood use

As already highlighted in Section 7.1.7, if additional measures that support the use of forest bioenergy with low associated GHG emissions can be explicitly linked to activities aimed at increasing the production of forest bioenergy, then substantive reductions in total GHG emissions can be achieved.

Such measures could include efforts towards the positive management of vegetation carbon balances, as part of initiatives aimed at increasing the supply/consumption of bioenergy. For example, in the case of forest bioenergy, these might include situations in which rotations applied to forest stands are extended as part of optimising biomass productivity, or the growing stock of existing degraded or relatively unproductive forests is enriched to enhance carbon stocks and productive potential. It is also possible to create new forest areas with the specific purpose of managing them for wood production, provided that forest carbon stocks on the land are increased as part of the conversion of non-forest land to forest stands, and that there are no associated detrimental indirect land-use changes.

Other measures could involve favouring the co-production of forest bioenergy in conjunction with additional material wood products, targeting the displacement of GHG-intensive counterfactual products, and encouraging the disposal of wood products at end of life with low impacts on GHG emissions.

Such types of supporting measure may be easier to encourage where the land areas involved and the biomass production are taking place within the EU region. However, extension to other regions may be possible if explicitly linked to requirements placed on consumers of bioenergy. It must be acknowledged that the consideration of supporting measures, as discussed in this report, is generalised, and the exact nature of any practical instruments aimed at achieving an explicit link between increased forest bioenergy consumption, and appropriate types of supporting measures, would require further development.

Despite the preceding discussion and the examples included, the clear and comprehensive articulation of what 'positive forest management and wood use regarding GHG emissions' might entail has proved elusive. This is due to two main reasons:

- In general, such positive actions involve a combination of a number of factors
- Often, the practical assessment and application of relevant actions will be site-specific and context-specific.

As a consequence, it is difficult to construct a simple list of "do's and don'ts" for forest management and wood use, just as it is difficult to specify 'low-risk' and 'high-risk' types of wood feedstock for use as bioenergy, in terms of GHG emissions (see Section 2.3.11). This is why, in Section 2.4, an approach based on a decision tree was proposed for the qualitative assessment of risks associated with bioenergy sources.

One possible approach to cataloguing positive (and indeed negative) approaches to forest management and wood use for the supply of forest bioenergy might involve the subsequent analysis of a decision tree such as in Figures 2.1a to 2.1d (see Section 2.4). The analysis would be based on tracing the low-risk (and moderate/high-risk) bioenergy pathways in the decision tree, then, based on the outcomes, specifying a set of (possibly ranked) options for positive/negative forest management and wood use, characterising good and bad practice, in the form of clear and generally applicable practical prescriptions. A very tentative version of such an analysis is shown in Table 7.1. The table gives examples of approaches to forest management or wood use that may be appropriate to emphasise in order to encourage the supply of forest bioenergy with low associated risks of GHG emissions. Examples are also given of approaches which, if given less emphasis or avoided, should reduce risks of high associated GHG emissions. However, the very preliminary and speculative nature of the analysis in Table 7.1 must be emphasised. It must also be noted that, in practice, it is very difficult to make completely black and white distinctions between low-risk and high-risk approaches to forest bioenergy supply.

The development of a comprehensive set of prescriptions, based on a full elaboration of an analysis such as illustrated in Table 7.1, would require considerable care. However, even before this could be attempted, it is first necessary to:

- Test the reliability and practicality of the decision tree approach such as illustrated in Figures 2.1a to 2.1d in Section 2.4
- Very probably, further elaborate the design of the decision tree to represent a wider and/or more detailed range of possible scenarios for forest management and wood use.

These areas of research and development are outside the scope of this present project but would appear to warrant some priority.

Table 7.1 Tentative and preliminary classification of approaches to forest management and wood use aimed at bioenergy supply with low risks of GHG emissions

More emphasis	Less emphasis	Avoid
Harvest residues (avoiding site depletion/degradation)		Harvest residues leading to site depletion/degradation
Early thinnings for bioenergy		
Salvage logging with restoration of previous forest cover		Salvage logging with conversion to biomass plantations
Afforestation avoiding iLUC and organic soils	Afforestation on organic soils	Afforestation leading to iLUC
Enrichment of growing stock as part of bioenergy production		
		Avoidable deforestation
Production from areas with high growth rates	Production from areas with low growth rates	Production from areas with very low growth rates
Introduction of management for production with co-production of bioenergy and materials and effective displacement and disposal at end of life	Introduction of management for production with co-production of bioenergy and materials and indifferent displacement and disposal at end of life	Introduction of management for production for bioenergy only
	Diversion of primary wood feedstocks for use as bioenergy instead of materials, where displacement and disposal at end of life would be effective	
Use of waste wood for bioenergy, avoiding diversion from use for materials, where displacement and disposal at end of life would be effective	Use of waste wood for bioenergy, that diverts from use for materials, where displacement and disposal at end of life would be effective	

7.4.6. Sustainability criteria for bioenergy sources

The types of supporting approaches outlined in Sections 7.4.3 to 7.4.5 could be applied to demonstrate compliance with sustainability criteria attached to sources of biomass used for energy. This would not constitute a completely new approach to sustainability criteria for biomass, and would not operate in isolation. Rather, criteria derived from the measures considered in Sections 7.4.3 to 7.4.5 would complement existing sustainability criteria already referred to in the biomass energy, agriculture and timber sectors, which in some cases are already well developed and numerous. The detailed development of complementary sustainability criteria (or enhancements to existing criteria), based on the approaches outlined in this section, is beyond the scope of this current project.

7.5. Possibilities for further research

This project has suggested avenues for further research on the topic of GHG impacts associated with bioenergy supply and consumption. Some key possibilities are outlined below.

Assessments similar to those made in this project could be made for a larger number of scenarios for the possible development of future EU policies towards energy, especially bioenergy (see Section 6.11.2). This research could include efforts to determine an optimal scenario, in terms of the levels and mix of bioenergy sources consumed for energy, with regard to impacts on GHG emissions. The refined scenario for bioenergy supply and consumption in the EU region, as sketched out in Section 6.10, would appear particularly worthy of further investigation.

A more comprehensive, multi-factorial sensitivity analysis could be carried out, with regard to possible options for both agricultural land management and forest management and wood use, involved in the supply of bioenergy (see Section 6.11.4). This research could include efforts to determine an optimal scenario, in terms of approaches to land management (e.g. optimal straw removal rate) and the utilisation of specific biomass feedstocks, with regard to impacts on GHG emissions.

As part of the qualitative assessment of forest bioenergy sources undertaken in Task 1 of this project, and elaborated in Section 2 of this final report, it is difficult to clarify whether increased consumption of forest bioenergy in the EU is likely to be achieved, in actual practice, through 'low risk' and 'moderate risk' scenarios for forest management and bioenergy production, such as increased extraction of harvest residues, or whether a wider range of scenarios with varying risk may be involved. A full systematic analytical assessment is required to determine whether scenarios are more or less likely to actually be involved in meeting increased demands for bioenergy.

The analysis undertaken in this project (Section 4.10.4), to assess whether specified levels of forest bioenergy supply are consistent with the fundamental forestry principle of sustainable yield, is worthy of further verification and refinement.

Scenarios could be assessed in which interactions between land-use change involved in the provision of increased levels of bioenergy and risks of iLUC are more explicitly investigated, although it should be noted that large uncertainties are likely to be associated with results for any such studies (see Section 6.11.5).

In the Task 1 report for this project, the suggestion was made (Section 5.6.1 of the Task 1 report) that one possible step towards managing risk associated with the increased use of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. This point has also been raised in this final project report, in Sections 2.3.13, 6.10.7, 7.1.6 and 7.4.4. The suggested approach may be worthy of further research and/or piloting. As part of any such exploration, some relatively recent developments with regard to such methodologies should be noted, in particular, the Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, proposed by the US EPA (EPA, 2014). As noted in Section 2.3.13, as part of future work, there may be merit in evaluating the EPA methodology alongside a specific implementation of the more flexibly-defined approach, as suggested in the Task 1 report, perhaps through consideration of suitable case studies, actual or hypothetical.

In principle, strategic assessments of significant initiatives involving increased consumption and supply of forest bioenergy could also be qualitative. This has led to the suggestion of an approach to screening bioenergy sources by making reference to a decision tree, as discussed in Sections 2.4 and 7.4.3. As with possible approaches to quantitative assessment, as part of further research, there may be merit in further developing and testing such an approach to qualitative assessment of bioenergy sources, possibly including the involvement of stakeholders with interests in the GHG impacts associated with bioenergy use.

The assessment and subsequent interpretation presented in this report have placed a notable emphasis on the potential role of additional measures, aimed at supporting positive approaches to forest management and wood use, in terms of achieving significant reductions in GHG emissions through the use of forest bioenergy (see Sections 4.8.3, 6.7.2, 6.7.3, 6.9.4, 6.10.7, 7.1.7 and 7.4.5). As explained in Section 7.4.5, the clear and comprehensive articulation of what 'positive forest management and wood use regarding GHG emissions' might entail, would appear to be an area of research and development warranting some priority.

Finally, as already raised in Section 6.11.8, ideally, a more comprehensive assessment of possible bioenergy policies is desirable, which, in addition to GHG emissions, would also consider impacts on (for example):

- The nutrient status and water-holding capacity of agricultural and forest land, potential erosion of agricultural soils
- The stability of forest sites (e.g. with respect to wind risk)

- The eutrophication of surrounding watercourses and lakes
- The biodiversity of agricultural land areas and forest stands and the wider surrounding landscape, and
- Economic and social factors.

Ideally, this sort of comprehensive sustainability assessment of specified levels bioenergy supply from agricultural and forest biomass sources is very desirable. However, such a study would require a large body of supporting data, which in many cases, most likely, would not be available. A comprehensive study of all possible impacts would also involve a much more significant set of supporting assumptions, which would be even more challenging to define and properly document for the purposes of transparency.

Appendix 1. References

ABRAF (2011) *Statistical Yearbook 2011: Base year 2010.* Brazillian Association of Forest Plantation Producers. Associação Brasileira de Produtores de Florestas Plantadas: Brazil. At: http://www.youblisher.com/p/200491-ABRAF-Statistical-yearbook-2011.

Agostini, A., Giuntoli, J. and Boulamanti, A. (2013) *Carbon accounting of forest bioenergy: conclusions and recommendations from a critical literature review*. European Commission - Joint Research Centre – Institute for Energy and Transport. EUR 25354 EN. Luxembourg: Publication Office of the European Union, 2013.

Alexandratos, N. and J. Bruinsma. (2012) *World agriculture towards 2030/2050: the 2012 revision.* ESA Working paper No. 12-03. FAO: Rome.

Allen, M.R., Frame, D.J., Huntingford, C., Jones, C.D., Lowe, J.A., Meinshausen, M. and Meinshausen, N. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163-1166.

Arkuszewska,A., Gaworska, M., Kluciñski, J., Kornatowska, B., Machnacz-Zarzeczna, M., Mikulowska, K., Richards, J. and Topczewska M. (2006) *Forests and forestry in European Union countries: the guide to forests and forest issues*. The State Forests Information Centre, Forest Research Institute: Poland.

Beets, P.N., Robertson, K., Ford-Robertson, J.B., Gordon, J. and Maclaren, J.P. (1999) Description and validation of C-change: a model for simulating carbon content in managed pinus radiata stands. *New Zealand Journal of Forestry Science*, **29**, 409-427.

Bradley, R.I., Milne, R., Bell, J., Jordan, C. and Higgins, A. (2005) A soil carbon and land use database for the United Kingdom. *Soil Use and Management*, **21**, 363-369.

B.C. Ministry of Forests, Mines and Lands (2010) *The State of British Columbia's Forests*, 3rd ed. Forest Practices and Investment Branch: Victoria, B.C. At: www.for.gov.bc.ca/hfp/sof/index.htm#2010_report.

Brentrup, F. and Palliére, C. (2008) GHG emissions and energy efficiency in European nitrogen fertiliser production and use. *Proceedings of the International Fertiliser Society*, No. 639: York, United Kingdom.

Britz, W. and Witzke, P. (2012) *CAPRI Model Documentation 2012*. Bonn University: Bonn. At: http://www.capri-model.org/docs/capri_documentation.pdf.

Cannell, M.G.R. and Dewar, R.C. (1995) The carbon sink provided by plantation forests and their products in Britain. *Forestry*, **68**, 35-48.

Christophel, D., Höllerl, S., Prietzel, J. and Steffens, M. (2015) Long-term development of soil organic carbon and nitrogen stocks after shelterwood- and clear-cutting in a mountain forest in the Bavarian Limestone Alps. *European Journal of Forest Research*, **134**, 623-640.

Christophel, D., Spengler, S., Schmidt, B., Ewald, J., and Prietzel, J. (2013) Customary selective harvesting has considerably decreased organic carbon and nitrogen stock in forest soils of the Bavarian Limestone Alps. *Forest Ecology and Management*, **305**, 167-176.

Coleman, K. and Jenkinson, D.S. (1999) *RothC-26.3 – A Model for the turnover of carbon in soil: Model description and windows users guide*. November 1999 issue: Lawes Agricultural Trust: Harpenden, UK.

Christie, J.M. and Lines, R. (1979) A comparison of forest productivity in Britain and Europe in relation to climatic factors. *Forest Ecology and management*, **2**, 75-102.

Couto, L., Nicholas, I. and Wright, L. (2011) *Short Rotation Eucalypt Plantations for Energy in Brazil*. IEA Bioenergy Task 43: Promising Resource Series 2001:02, 1-16.

Dewar, R.C. (1991) Analytical model of carbon storage in the trees, soils, and wood products of managed forests. *Tree Physiology*, **8**, 239-258.

Dewar, R.C. (1990) A model of carbon storage in forests and forest products. *Tree Physiology*, **6**, 417-428.

Diochon, A., Kellman, L. and Beltrami, H. (2009) Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens Sarg.*) forest chronosequence. *Forest Ecology and Management*, **257**, 413-420.

Edwards, P.N. and Christie, J.M. (1981) Yield *models for forest management*. Forestry Commission Booklet 48. Forestry Commission: Edinburgh.

EEA (2013) *EU bioenergy potential from a resource efficiency perspective*. EEA Report 6/2013. European Environment Agency, Publications of the European Union: Luxembourg. At: http://www.eea.europa.eu/publications/eu_bioenergy_potential.

EEA (2011) *Opinion of the EEA Scientific Committee on greenhouse gas accounting in relation to bioenergy*. At: http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas/view.

EEA (2007) *Environmentally compatible bio-energy potential from European forests.* EEA Technical Report No 2007/12. European Environment Agency: Copenhagen. At: http://www.efi.int/files/attachments/eea_bio_energy_10-01-2007_low.pdf.

Elbersen, B., Fritsche, U. Petersen, J.-E., Lesschen, J.P., Böttcher, H. and Overmars, K. (2013) Assessing the effect of stricter sustainability criteria on EU biomass potential. *Biofuels, Bioproducts and Biorefining*, **7**, 173–192.

Elbersen, B.S., Staritsky, I., Hengeveld, G., Schelhaas, M.J., Naeff, H. and Böttcher, H. (2012) Atlas of EU biomass potentials. Deliverable 3.3: *Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources*. Report for Task 3 in Biomass Futures project. At: http://www.biomassfutures.eu/work_packages/WP3 Supply/D_3_3__Atlas_of_technical_and_economic_biomass_potential_FINAL_Feb_2012.pdf.

ELCD (2014) *European Life Cycle Database*. European Commission, Directorate-General Joint Research Centre, Institute for Environment and Sustainability (JRC-IES), European Platform on Life Cycle Assessment (EPLCA). At: http://eplca.jrc.ec.europa.eu/?page_id=126.

EPA (2014) *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources.* United States Environmental Protection Agency: Washington DC.

Ericsson, K. and Nilsson, L.J. (2006) Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, **30**, 1-15.

European Commission (2013) *Prospects for Agricultural Markets and Income in the EU 2013-2023*. Directorate-General for Agriculture and Rural Development: Brussels.

European Commission (2012) *Carbon Impacts of biomass consumed in the EU:* ENER/C1/427-2012, Tender Specifications. Directorate-General for Energy: Brussels.

European Council (2014) *Conclusions on the 2030 Climate and Energy Policy Framework.* SN79/14, Brussels, Belgium.

FAO (2010) *Global Forest Resources Assessment 2010: Main report*. FAO Forestry paper 163. Food and Agriculture Organization of the United Nations: Rome. At: http://www.fao.org/forestry/fra/fra2010/en.

Forestry Commission (2014) *Forestry Statistics 2014: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. At: www.forestry.gov.uk/forestry/infd-7aqdgc.

Forestry Commission (2012) *Forestry Statistics 2012: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. At: www.forestry.gov.uk/forestry/infd-7aqdgc.

Forestry Commission (2011) *Forestry Statistics 2011: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. At: www.forestry.gov.uk/forestry/infd-7aqdgc.

GEA (2012) *Global Energy Assessment - Toward a Sustainable Future,* Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis: Laxenburg, Austria.

Goh, C.S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., Heinimö, J., Nikolaisen, L., Schouwenberg, P.-P., Bradley, D., Hess, R., Jacobson, J., Ovard, L., Deutmeyer, M. (2013) Wood pellet market and trade: a global perspective. *Biofuels, Bioproducts and Biorefining,* **7**, 24-42.

Grassi G. (2011) *Joint Research Center (JRC) LULUCF tool,* version December 2011. At: ftp://mars.jrc.ec.europa.eu/Afoludata/Public/DS242/JRC_LULUCF_TOOL_(8%20Dec%20 2011).xlsx.

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R.K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van de Hove, S., Vermeire, T., Wadhams, P. and Searchinger, T. (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, **45**, 18-23.

Hargreaves, K.J., Milne, R., and Cannell, M.G.R. (2003) Carbon balance of afforested peatland in Scotland. *Forestry*, **76**, 299-317.

Hijmans, R.J., S.E. Cameron, S.E., J.L. Parra, J.L. P.G. Jones, P.G. and A. Jarvis, A. (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, **25**, 1965-1978.

Holtsmark, B. (2015) Calculating the global warming potential of CO_2 emissions from wood fuels. *GCB Bioenergy*, **7**, 195-206.

Holtsmark, B. (2013) Boreal forest management and its effect on atmospheric CO_2. *Ecological Modelling*, **248**, 130-134.

Holtsmark, B. (2012a) Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, **112**, 415-428.

Holtsmark, B. (2012b) The outcome is in the assumptions: analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy*, **5**, 467-473.

IISA (2014) *Global Emissions Model for integrated Systems (GEMIS v.4.9)*. International Institute for Sustainability Analysis and Strategy: Darmstadt, Germany. At: http://www.iinas.org/gemis.html.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). IPCC: Switzerland. At: http://www.ipcc-nggip.iges.or.jp/public/wetlands/.

IPCC (2008) *2006 Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories, Vol. 2: Energy.* Chapter 3: Mobile combustion. Garg, A., Kazumari, K. and Pulles, T. (eds.). Institute for Global Environmental Strategies: Hayama, Japan, corrected June 2010. At: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf.

IPCC (2007) *2006 Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories, Vol. 2: Energy.* Chapter 2: Stationary combustion. Garg, A., Kazumari, K. and Pulles, T. (eds.). Institute for Global Environmental Strategies: Hayama, Japan, corrected April 2007. At: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf.

IPCC (2006) *2006 Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories, Vol. 2: Energy.* Chapter 1: Introduction. Garg, A., Kazumari, K. and Pulles, T. (eds.). Institute for Global Environmental Strategies: Hayama, Japan. At: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf.

IPCC (1996) *Climate Change 1995: the science of climate change,* Technical Summary, B8. Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds.). Cambridge University Press: Cambridge. At: https://www.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf.

ISO (2006) 14044:2006. *Environmental management – Life cycle assessment – Requirements and guidelines*. International Organization for Standardization (ISO), Geneva.

Jenkins, T.A.R, Mackie, E.D., Matthews, R.W., Miller, G., Randle, T.J. and White, M.E. (2014) *FC woodland carbon code: carbon assessment protocol*. Forestry Commission: Edinburgh.

Jenkinson, D.S. and Rayner, J.H. (1977) The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science*, **123**, 298-305.

Johnson, K., Scatena, F.N. and Pan, Y. (2009) Short- and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest. *Forest Ecology and Management*, **259**, 1262-1267.

Jonard M., Fürst A., Verstraeten A., Thimonier A., Timmermann V., Potočić N., Waldner P., Benham S., Hansen K., Merilä P., Ponette Q., de la Cruz A., Roskams P., Nicolas M., Croisé L., Ingerslev M., Matteucci G., Decinti B., Bascietto M., Rautio P. (2015) Tree mineral nutrition is deteriorating in Europe. *Global Change Biology*, **21**, 414-430.

JRC (2010) *International Reference Life Cycle Data System (ILCD) Handbook- Detailed Guidance*. European Commission, Joint Research Centre, Institute for Environment and Sustainability. First Edition March 2010. EUR 24708 EN. Luxembourg: Publication Office of the European Union, 2010.

Knopf, B., Chen, Y-H.H., de Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K. and van Vuuren, D.P. (2013) Beyond 2020 – strategies and costs for transforming the European energy system. *Climate Change Economics*, **4**, Suppl. 1: 1340001.

Kröger, M. (2012) *Global tree plantation expansion: a review*. ICAS review paper series No. 3. Initiatives in Critical Agrarian Studies (ICAS): The Hague, Netherlands.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Saw, C.H., Rampley, G.J., Smyth, C., Simpson, B.M., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J. (2009) CBM-CFS3: A model of carbon dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling*, **220**, 480-504.

Laborde, D. (2011) *Assessing the land use change consequences of European biofuel policies.* Report for DG Trade of the European Commission. International Food Policy Research Institute: Washington DC.

Lamers, P. and Junginer, M. (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts, and Biorefining*, **7**, 373-385.

Lavers, G.M. (1983) *The strength properties of timber*. 3rd, revised edition. Building Research Establishment Report. HMSO: London.

Leip A., Leach A., Musinguzi P., Tumwesigye T., Olupot G., Tenywa J.S., Mudiope J., Hutton O., d S Cordovil C.M., Bekunda M. and Galloway J. (2014) Nitrogen-neutrality: a step towards sustainability. *Environmental Research Letters*, **9**, 115001.

Lesschen, J.P., van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O. (2011) Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology,* **166–167**, 16-28.

LIIB (2012) *Low Indirect Impact Biofuel methodology – version zero.* Ecophys, EPFL and WWF International. At: http://www.ecofys.com/files/files/12-09-03-liib-methodology-version-0-july-2012.pdf.

Loulou, R. and Labriet, M. (2008) ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Computational Management Science*, **5**, 1-2, 7-40.

Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., Eggers, J., Leek, N., Oldenburger, J., Asikainen, A. and Anttila, P. (2010) *EUwood - Real potential for changes in growth and use of EU forests.* Final report. University of Hamburg: Hamburg, Germany.

Marland, G. and Schlamadinger, B. (1999) The Kyoto Protocol could make a difference for the optimal forest-based CO_2 mitigation strategy: some results from GORCAM. *Environmental Science and Policy*, **2**, 111–124.

Marland, G. and Schlamadinger, B. (1995) Biomass fuels and forest management strategies: How do we calculate the greenhouse-gas emissions benefits? *Energy*, **20**, 1131-1140.

Matthews, G.A.R. (1993) *The carbon content of trees*. Forestry Commission Technical Paper 4. Forestry Commission: Edinburgh.

Matthews, R.W. (1996) The influence of carbon budget methodology on assessments of the impacts of forest management on the carbon balance. In Apps, M.J. and Price, D.T. (eds.). Forest ecosystems, forest management and the global carbon cycle. *NATO ASI Series* **I 40**. Springer-Verlag: Berlin, 233-243.

Matthews, R.W. (1994) *Towards a methodology for the evaluation of the carbon budget of forests*. In: Kanninen, M. (ed.) Carbon balance of the world's forested ecosystems: towards a global assessment. Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 105-114. Painatuskeskus: Helsinki.

Matthews, R.W. (1991) *Biomass production and storage by British Forests.* In: Aldhous, J.R. (ed.). Wood for energy: the implications for harvesting, utilisation and marketing. Proceedings of a discussion meeting, Heriot-Watt University, Edinburgh, 5-7 April 1991. Edinburgh: Institute of Chartered Foresters, 1991, 162-177.

Matthews, R., Sokka, L., Soimakallio, S., Mortimer, N., Rix, J., Schelhaas, M-J., Jenkins, T., Hogan, G., Mackie, E., Morris, A. and Randle, T. (2014a) *Review of literature on biogenic carbon and life cycle assessment of forest bioenergy.* Final Task 1 report, EU DG ENER project ENER/C1/427, 'Carbon impacts of biomass consumed in the EU'. Forest Research: Farnham. At: http://ec.europa.eu/energy/sites/ener/files/2014_biomass_forest_research_report_.pdf.

Matthews, R., Mortimer, N., Mackie, E., Hatto, C., Evans, A., Mwabonje, O., Randle, T., Rolls, W., Sayce, M. and Tubby, I. (2014b) *Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: Forests*. Final Report for Department of Energy and Climate Change. Revised 2014. Forest Research: Farnham.

Matthews, R., Malcolm, H., Buys, G., Henshall, P., Moxely, J., Morris, A., and Mackie, E. (2014c) *Changes to the representation of forest land and associated land-use changes in the 1990-2012 UK Greenhouse Gas Inventory*. Report to Department of Energy and Climate Change, Contract GA0510, CEH: Edinburgh.

Matthews, R.W. and Broadmeadow, M.S.J. (2009) *The potential of UK forestry to contribute to Government's emissions reduction commitments*. In: Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds.) Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office: Edinburgh, 139-161.

Matthews, R.W. and Mackie, E.D. (2006) *Forest Mensuration: A Handbook for Practitioners*. Second edition. Forestry Commission: Edinburgh.

Matthews, R.W. and Duckworth, R.R. (2005) *BSORT: a Model of Tree and Stand Biomass Development and Production in Great Britain.* In: Imbabi, M.S. and Mitchell, C.P. (eds.) Proceedings of World Renewable Energy Congress (WREC 2005), 22-27 May 2005, Aberdeen, UK. Elsevier: Oxford, pp. 404-409.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J. and Allen, M.R. (2009) Greenhouse gas emissions targets for limiting atmospheric warming to 2 °C. *Nature*, **458**, 1158-1163.

Mohren, G.M.J., Garza Caligaris, J.F., Masera, O., Kanninen, M., Karjalainen, T. and Nabuurs, G.-J. (1999) *CO_2FIX for Windows: a dynamic model of the CO_2 fixation in forest stands*. Institute for Forestry and Nature Research (The Netherlands), Instituto de Ecologia (UNAM, Mexico), Centro Agronomico Tropical de Investigacion y Ensenanza (Costa Rica) and European Forest Institute (Finland).

Mohren, G.M.J. and Klein Goldewijk, C.G.M. (1990). CO_2FIX: a dynamic model of the CO_2-fixation in forest stands. "De Dorschkamp", Research Institute for Forestry and Urban Ecology Report 624: Wageningen.

Morison, J., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012) *Understanding the carbon and greenhouse gas balance of forests in Britain.* Forestry Commission Research Report 18. Forestry Commission: Edinburgh, 1-149.

Nabuurs, G.-J. (1996) Significance of wood products in forest sector carbon balances. In Apps, M.J. and Price, D.T. (eds.). Forest ecosystems, forest management and the global carbon cycle. *NATO ASI Series* **I 40**. Springer-Verlag: Berlin, 245-256.

Natural Resources Canada (2015) *Statistical data, forest resources*. At: http://cfs.nrcan.gc.ca/statsprofile.

Paillet, Y., Chevalier, H., Lassauce, A., Vallet, P., Legout, A., and Gosselin, M. (2013) Integrating fertilisation and liming costs into profitability estimates for fuel wood harvesting: A case study in beech forests of eastern France. *Biomass and Bioenergy*, **55**, 190-197.

Panoutsou, C., Labalette, F. (2007) Cereals straw for bioenergy and competitive uses. In: *Proceedings of the Expert Consultation: Cereals Straw Resources for Bioenergy in the European Union*, Pamplona, 18-19 October 2006. European Commission, Directorate General, Joint Research Centre, Institute for Environment and Sustainability. EUR 22626 EN. Luxembourg: Office for Official Publications of the European Community, 2007.

Pedroli, B., Elbersen, B., Frederiksen, P., Grandin, U., Heikkilä, R., Krogh, P.H., Izakovičová, Z., Johansen, A., Meiresonne, L., Spijker, J. (2013) Is energy cropping in Europe compatible with biodiversity? – Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes. *Biomass and Bioenergy*, **55**, 73-86.

Powlson, D.S., Glendining, M.J., Coleman, K., Whitmore, A.P. (2011) Implications for Soil Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agronomy Journal,* **103**, 279-287.

Repo, A., Känkänen, R., Tuovinen, J-P., Antikainen, R., Tuomi, M., Vanhala, P. and Liski, J. (2012) Forest bioenergy climate impact can be improved by allocating forest residue removal. *GCB Bioenergy*, **4**, 202-212.

Repo, A., Toumi, M. and Liski, J. (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy*, **3**, 107-115.

Robertson, K., Ford-Robertson, J., Matthews, R.W. and Milne, R. (2003) *Evaluation of the C-FLOW and CARBINE carbon accounting models.* In: UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities. Report, April 2003. DEFRA contract EPG1/1/160, CEH No. C01504. At: http://ecosystemghg.ceh.ac.uk/docs/2006andOlder/DEFRA_Report_2003_Section03_web.pdf.

RSPB (2012) *Dirter than coal? Why Government plans to subsidise burning trees are bad news for the planet*. Joint statement by RSPB, Friends of the Earth and Greenpeace. At: https://www.rspb.org.uk/Images/biomass_report_tcm9-326672.pdf.

Scarlat, N., Martinov, M., Dallemand, J.-F. (2010) Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Management*, **30**, 1889–1897.

Schelhaas, M.J., Eggers, J., Lindner, M., Nabuurs, G.j., Pussinen, A., Païvinen, R., Schuck, A., Verkerk, P.J., van der Werf, D.C. and Zudin, S., (2007) *Model documentation for the European Forest Information Scenario model (EFISCEN 3.1.3)*. EFI Technical Report 26. Alterra: Wageningen.

Schlamadinger B. and Marland, G. (1996) Carbon implications of forest management strategies. In Apps, M.J. and Price, D.T. (eds.). Forest ecosystems, forest management and the global carbon cycle. *NATO ASI Series* **I 40**. Springer-Verlag: Berlin, 217-232.

Schulze, E.-D., Körner, C., Law, B.E., Haberl, H. and Luyssaert, S. (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, **4**, 611-616.

Searchinger, T. (2012) *Sound principles and important inconsistencies in the 2012 UK bioenergy strategy.* Non-peer reviewed statement. At: https://www.rspb.org.uk/Images/Searchinger_comments_on_bioenergy_strategy_SEPT_2012_tcm9-329780.pdf.

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J. (2014) Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change,* **4**, 806-810.

Smith P, Smith J, Flynn H, Killham K, Rangel-Castro, I., Foereid, B., Aitkenhead, M., Chapman, S., Towers, W., Bell, J., Lumsdon, D., Milne, R., Thomson, A., Simmons, I., Skiba, U., Reynolds, B., Evans, C., Frogbrook, Z., Bradley, I., Whitmore, A. and Falloon, P. (2007) *ECOSSE: Estimating Carbon in Organic Soils: Sequestration and Emissions.* Scottish Executive: Edinburgh, 177pp.

Taghizadeh-Toosi, A., Christensen, B.T., Hutchings, N.J., Vejlin, J., Kätterer, T., Glendining, M., Olesen, J.E. (2014) C-TOOL: A simple model for simulating whole-profile carbon storage in temperate agricultural soils. *Ecological Modelling* **292**, 11-25.

Ter-Mikaelian, M.T., Colombo, S.J. and Chen, J. (2015) The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry*, **113**, 57-68.

Thompson, D. and Matthews, R. (1989). CO_2 in trees and timber lowers the greenhouse effect. *Forestry and British Timber,* **18**, 19-24.

Tóth, G., Jones, A. and Montanarella, L. (eds.) (2013) *LUCAS topsoil survey - methodology, data and results.* Reference Report by the Joint Research Centre of the European Commission, EUR 26102 EN. Luxembourg: Publication Office of the European Union, 2013.

UNECE and FAO (2012) *Data on prices and volumes of wood imports and exports in EU Member States* (extract). Datasets can be found at: www.unece.org/forests/output/prices.html.

UNECE and FAO (2011) *The European Forest Sector Outlook Study II: 2010-2030 (EFSOS II)*. Publishing Service, United Nations: Geneva.

UNFCCC (1992) *United Nations Framework Convention on Climate Change*. At: http://unfccc.int.

Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A.H., Klimont, Z. and Oenema, O. (2009) Integrated assessment of nitrogen emissions from agriculture in EU-27 using MITERRA-Europe. *Journal of Environmental Quality*, **38**, 402-417.

Verkerk, P.J., Anttila, P., Eggers, J., Lindner, M. and Asikainen, A. (2011) The realisable potential supply of woody biomass from forest in the European Union. *Forest Ecology and Management*, **261**, 2007-2015.

Vleeshouwers, L.M. and Verhagen, A. (2002) Carbon emission and sequestration by agricultural land use: a model study for Europe. *Global Change Biology*, **8**, 519–530.

Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, B., Recchia, C. and Saah, D. (2010) *Massachussets biomass sustainability and carbon policy study*. Manomet Center for Conservation Sciences: Brunswick, Maine. USA.

Walmsley, J.D., Godbold, D.L. (2010) Stump Harvesting for Bioenergy – A Review of the Environmental Impacts. *Forestry,* **83**, 17-38.

Wit, de M.P., Lesschen, J.P., Londo, M.H.M., Faaij, A.P.C. (2014) Environmental impacts of integrating biomass production into European agriculture. *Biofuels, Bioproducts and Biorefining*, **8**, 374-390.

Yamulki, S., Anderson, R., Peace, A., & Morison, J.I.L. (2013) Soil CO_2, CH_4, and N_2O fluxes from an afforested lowland raised peatbog in Scotland: implications for drainage and restoration. *Biogeosciences,* **10**, 1051-1065.

Appendix 2. Glossary

There are many terms used in the evaluation and reporting of greenhouse gas emissions associated with the production and utilisation of biomass and bioenergy products that have apparently specialised meanings. In some instances, these terms have strict definitions that are broadly accepted and used. However, in other instances, there are terms which are less well-defined and often have ambiguous or unclear meanings. This situation has considerable potential for creating confusion for those engaged in this area of work and in subsequent debates over the interpretation of the results of such work. It is not the purpose of this glossary to impose strict definitions. Instead, the glossary is intended to establish reasonably precise terms as used in this project and, where necessary, to point out discrepancies in their former, less defined usage. Given the context of this project, all terms are explained here in the context of the evaluation of the global consequences of policies for the greenhouse gas dynamics of utilising biomass in general by means of life cycle assessment. Note that some terms in this glossary are included for consistency with the earlier Task 1 report for this project. Following the glossary, a table is provided in which units of measurement are also defined.

Glossary of terms

Absolute GHG emissions	In the context of this report absolute GHG emissions can be defined as the total GHG emissions occurring in association with a clearly defined activity. Absolute GHG emissions are calculated as the sum of all GHG emissions crossing a system boundary. It must be stressed that, strictly, calculations of absolute GHG emissions are not made in comparison with some other possible activity and do not involve calculating GHG emissions compared with any sort of reference/baseline value or reference/baseline projection for GHG emissions.
Additionality	Additionality refers to the positive net benefits in terms of climate change mitigation directly attributable to a mitigation activity or project. The concept generally refers to net greenhouse gas emissions reductions over and above that which would have occurred anyway in the absence of a given mitigation activity or project.
Afforestation	The direct human-induced conversion of land that has not been forested in the recent past to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.
Albedo	Albedo refers to the reflectivity or reflection coefficient of the Earth's surface, which is measured as the ratio between solar radiation reflected back from the surface, and the original solar radiation incident upon it.
Anthropogenic climate change	Climate change attributable to human activity.
Arboricultural arisings	Woody biomass, sometimes used for energy, derived from the management of isolated trees, small groups of trees, urban and street trees, and hedgerows. Sometimes referred to as "landscape care wood".

Attributed GHG emissions	In the context of this report attributed GHG emissions are defined as GHG emissions calculated and reported as part of an attributional LCA study. Results for GHG emissions may be "attributed" to a single product or service, or may be allocated amongst two or more co-products or services (depending on the details of the system being studied). Attributional GHG emissions are defined to distinguish them from absolute GHG emissions and consequential GHG emissions.
Attributional life cycle assessment	An approach to life cycle assessment in which natural resource and environmental impacts, such as greenhouse gas emissions, are assigned to functional units under consideration. The purpose intended, the approach adopted and the results obtained are different from those of consequential life cycle assessment.
Bark	The outer layers of the stems and branches of woody plants and trees.
Baseline	In order to estimate the benefits of a climate change mitigation activity in terms of "additional" greenhouse gas emissions reductions, it is necessary to compare the levels of emissions and removals estimated for the mitigation activity with those estimated assuming the mitigation activity is not carried out. The reference estimate or trajectory referred to in such a comparison is known as a baseline.
Bioenergy	There is no universally-agreed and strictly applied definition of the term "bioenergy" other than general recognitions that it is energy which is derived from recently growing organic material. Depending on the context, the form of energy so derived can be specified differently or collectively as solid, liquid and/or gaseous fuel in its original state (identified as primary energy), or in its final state such as heat, electricity, etc. (recognised as delivered energy). Furthermore, the term "bioenergy" can often be used interchangeably with the phrase "biomass energy". In common with its usage in many studies addressed in the literature review undertaken in Task 1, which comprises the *qualitative assessment* conducted in this particular project, bioenergy as defined in the Task 1 report refers to a narrower definition of "biomass which is used to generate energy, generally in the form of heat or power". In this report, which concentrates on the *quantitative assessment*, a broader definition of bioenergy has been adopted for consistency with the terminology used in the VTT-TIAM model. For this purpose, bioenergy is taken to refer to sources of energy derived from recent organic material consisting of the following specific categories: • Biomass; predominantly composed of wood obtained from forests, agriculture and other primary sources, and straw obtained as an agricultural residue. • Bioliquids; mainly consisting of biofuels that can be used to displace liquid fuels derived from fossil fuels. • Biogas; biomethane and synthetic natural gas produced by a number of different processes from a variety of different types of biomass. • Biowaste; chiefly domestic, commercial and industrial solid wastes.

Bioenergy feedstock	A specific source of bioenergy used as the input to an energy conversion process.
Biofuel	These are liquid and gaseous fuels obtained from feedstocks sourced from organic material. It is a term used by the European Commission specifically to refer to biomass-derived fuels that are predominantly used in transport. This term is sometimes used interchangeably and confusingly with bioenergy (see above) which the European Commission specifies as heating, cooling and electricity generated from biomass.
Biogenic carbon	Carbon contained in or derived from recently living organic material, as distinct from fossil carbon. This includes carbon in the living and dead biomass of vegetation, including the woody biomass of trees.
Biologically mature forest	Areas of forest where the trees have reached an age where net growth in volume has effectively ceased and further growth, without some form of environmental change or regeneration, will not occur. Such forest may or may not have high carbon stocks, depending on certain factors, e.g. the extent of natural disturbances.
Biomass	Biological material derived from living, or recently living organisms. In the context of this report, this is taken to mean the biomass of vegetation.
Biomass cascading	The active management of harvested wood through a sequence of uses, with ultimate disposal through burning with energy recovery. An example of thoroughly-implemented biomass cascading might involve the use of wood in sawn timber products, then re-use or recycling as a feedstock for wood-based panels, and burning as a source of energy only ultimately after repeated use in solid products.
Black liquor	A by-product of paper manufacture, specifically from the digestion of pulpwood into paper pulp, to remove lignin, hemicelluloses and other compounds. It consists of a mixture of lignin, hemicellulose and chemicals involved in the extraction process. Black liquor contains a significant proportion of the energy content of the wood feedstock and is a potential source of bioenergy.
Boreal forests	Broadly defines forests found to the south of the Arctic, but north of the temperate regions, including Taiga in northern Russia.
Branchwood	Generally considered to be the portion of above ground woody biomass of a tree which is not defined as stemwood. May contain branches and stem tops below a certain diameter.
"Business as usual" scenario	A scenario describing specified activities, services and processes, and associated flows, e.g. of energy and GHG emissions, intended to represent the current and future situation in the absence of policy interventions other than those already being implemented.
Calorific value, net calorific value	The quantity of heat produced by the complete combustion of a given amount (i.e. mass) of a substance. Calorific values are typically expressed in units of joules per gram or megajoules per kilogram (MJ kg^{-1}). The net calorific value of an energy source is sometimes also referred to as the lower heating value. Net calorific value represents the quantity of heat produced by the complete combustion of a given amount of a substance, allowing for any moisture content, such as in the case of air-dry wood.
Carbon content	The proportion of the dry mass of a material composed of carbon.

Carbon debt	This term is not favoured in this report and generally is not referred to. The term is used with different meanings by different authors. Broadly speaking, it refers to reductions in carbon stocks or loss of potential carbon sequestration in forest areas, which occur as a result of management interventions such as harvesting.
Carbon neutrality	This term is not favoured in this report and generally is not referred to. Broadly speaking, the concept is concerned with the achievement of zero net carbon emissions by compensating for GHG emissions with an equivalent amount of sequestration or offsetting.
Carbon sequestration	In the context of agriculture, forestry and bioenergy, this is the process by which carbon dioxide is removed from the atmosphere by the growth of vegetation and carbon is retained in the living and dead biomass of vegetation, litter and soil organic matter. For sequestration to be said to have occurred, there must have been a reservoir which has increased in carbon stocks. Taking the example of a stand of trees, suppose a stand of trees grows by X tonnes of carbon per year, through removal of atmospheric carbon dioxide, but this is balanced by reductions in carbon stocks due to harvesting in another stand, so that the total quantity of carbon stocks in the forest stands does not change. Sequestration is not occurring because there is no increase in carbon stocks. In order to focus on changes of lasting consequence, most commentators would ignore sequestration that takes place on a daily, seasonal or even annual basis, and consider only activities that show a trend over longer time intervals.
Carbon sink	Any process, activity or mechanism which removes carbon dioxide from the atmosphere and retains the carbon in a reservoir. (See "carbon sequestration").
Carbon stock	In the context of agriculture, forestry and bioenergy, a carbon stock is an amount of carbon sequestered in the living and dead biomass of vegetation, litter and soil organic matter comprising an agricultural field, a whole agricultural system, forest stand of whole forest.
Carbon dioxide equivalent (CO_2 equivalent)	A unit used to express GHG emissions in terms of the equivalent amount of CO_2. Since each non-CO_2 GHG gas has a different warming effect on the atmosphere, the weightings, also called Global Warming Potentials (GWPs) reflect this. The latest GWP values published by the IPCC in 2007, based on a 100 year time horizon, are 25 for methane and 298 for nitrous oxide. For example, this means that 1 tonne of methane would be expressed as 25 tonnes CO_2-equivalent.
Complementary felling	In the context of this report, complementary felling is a term used by some commentators to refer to a type of additional tree harvesting in forest areas in order to increase the supply of forest bioenergy. Specifically, when certain types of forest stand are clearfelled for timber production, some trees unsuitable for use as timber may be retained on site. Complementary felling involves the additional felling of some or all of the otherwise unsuitable trees for utilisation as bioenergy.
Consequential GHG emissions	In the context of this report consequential GHG emissions can be defined as the total change in GHG emissions that occurs (or would occur) as a consequence of a change (or possible/proposed change) to an existing activity. As such, consequential GHG emissions are typically calculated and reported as part of a consequential LCA study.

Consequential life cycle assessment	This is a form of life cycle assessment in which the complete natural resource and environmental impacts, such as greenhouse gas emissions, are determined for a given proposed action, decision or policy. The purpose intended, the approach adopted and the results obtained are different from those of "attributional life cycle assessment".
Coppice	Trees felled close to the ground so as to produce shoots from the resulting stumps, giving rise to poles and sticks which are then harvested over successive rotations. (See "High forest".)
Continuous cover silviculture	A system for the management of forest areas, generally aiming to maintain tree canopy cover in forest stands. Large-scale clearfelling is avoided, although there may be some small patches of clearfelling. Typically, stands managed according to continuous cover silviculture have a more complex structure (in terms of species composition and/or age distribution and size distribution), compared with even-aged forest stands managed according to a system involving periodic clearfelling and replanting/regeneration.
Counterfactual	For assessments of GHG emissions of bioenergy sources, involving changes to land management or bioenergy use, it is essential to characterise realistic and justifiable "counterfactuals". This is elaborated below for the case of forest bioenergy. For land use (generally involving forest management in this context), the counterfactual describes how forest areas would be managed if the forest management were not to be changed (typically, a "business as usual" scenario). For harvested wood products, counterfactuals involve the "business as usual" patterns for wood use, and also a set of assumptions about what energy sources and materials might be used instead of forest bioenergy and harvested wood products. When defining such counterfactuals, it is important to recognise that the use of wood for material and fibre products, and as a feedstock for chemicals, may be as or more important as forest bioenergy in the future.

Direct GHG emissions	In LCA, direct GHG emissions are those which arise specifically from a given activity which is under particular investigation. Such emissions are distinguished from indirect GHG emissions which arise from activities which are associated with the activity under investigation. In terms of LCA, direct emissions can be distinguished from indirect emissions by specification of a systems boundary. However, since systems boundaries can be drawn around different spatial locations (and, indeed, over different temporal periods) depending on the LCA goal, or "question", it is possible to encompass either single or groups of interconnected activities, thereby changing what is referred to as direct as opposed to indirect emissions. Hence, the particular context of the LCA will determine the precise meaning of the term "direct GHG emissions". In relation to quantitative assessment undertaken in this project, direct GHG emissions refer to those emissions directly due to the use (i.e. combustion) of an energy source such as coal, oil, natural gas, bioenergy, etc. In the case of forestry systems, it should be noted that direct GHG emissions associated with bioenergy obtained from forests consist of carbon dioxide emissions from carbon stock changes (or changes in carbon sequestration) in these forest resulting from the provision of such wood and the eventual GHG emissions of the eventual burning of this wood or any fuels derived from this wood. In this project, all GHG emissions associated with the provision and combustion of fuels obtained from other sources of wood and all other biomass are addressed as indirect GHG emissions.
End of Life	This is the final phase in the life of a product which may consist of disposal or recycling.
EU Member States	States that are party to treaties of the European Union (EU). The member states are thereby subject to obligations and privileges of EU membership. As of 1 July 2013, there are 28 member states: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.
EU Renewable Energy Directive (RED)	The EU Renewables Directive (2009/28/EC) mandates levels of renewable energy use within the European Union. The directive requires Member States to produce 20% of energy consumption (across the EU) from renewable sources by 2020.
EU15	The 15 Member States of the European Union consisting of: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden and the United Kingdom. Collectively the EU15 as a body is a signatory to the Kyoto Protocol.
EU27	The 27 Member States of the European Union consisting of: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

Feedstocks	In the context of this report, feedstocks are fuel inputs to energy generation processes, for example, coal, oil or agricultural or woody biomass. In the case of woody biomass, it is possible to distinguish different types of feedstock depending on how they are derived from harvested trees, e.g. branchwood, stemwood, small roundwood, off cuts and co-products from production of sawn timber, and waste wood at end of life. Wood energy feedstocks may also take processed form such as wood chips, pellets and briquettes. It should be noted that the term "feedstock" is sometimes used to refer to inputs of materials or chemicals to industrial manufacturing processes.
Final energy consumption	Final energy consumption represents all energy supplied to final consumers within a specified region for all energy uses, i.e. allowing for losses from transportation, conversion and other inefficiencies related to use of the energy within the specified region.
Finished wood products	The products made from wood as a result of processing of raw harvested wood. Examples include sawn wood and wood-based panels.
Forest bioenergy	Any biomass extracted from forests that is used to produce energy in the form of heat and power (i.e. not including liquid transport fuels). The biomass may be harvested directly from forests, or may be supplied as a by-product of the manufacture of solid wood products (e.g. offcuts from sawmilling) or may be derived from waste wood sources (e.g. solid wood products disposed of at end of life).
Forest biomass	Biomass contained in, or extracted from, forests, typically in the form of woody material.
Forest carbon	A general term referring to carbon stocks and carbon dynamics associated with forest systems.
Forest carbon dynamics	The flows of carbon within a forestry system due to processes such as growth and decay and effects due to management operations, e.g. planting, thinning and felling.
Forest ecosystem	In a forest, the communities of different organisms in conjunction with the wider environment when interacting as a system.
Forest growing stock	The population of trees forming an area of forest. Growing stock is sometimes expressed as the number of trees per hectare or standing stem volume per hectare of different tree species forming a forest area. Standing biomass and carbon stocks may also be referred to when considering growing stock.
Forest harvesting	Any activity involving the felling of trees for the purposes of extraction of timber and/or biomass. Harvesting is often differentiated into thinning and clear felling (or clear cutting). Thinning involves felling small proportions of the trees in an area during the growth of the stand to give the remaining trees more resources. Clear-felling or clear-cutting involves felling an entire stand when the trees have reached a particular target, e.g. maximum average volume growth or mean diameter.
Forest management	The process of managing a forest, usually to a plan detailing the areas and programmes for tree establishment, tending and prescribed forest harvesting events, along with wider management of the biodiversity and social aspects of a forest.

Forest scrub	The term scrub does not have a standardised meaning. In the context of this report, scrub refers to areas of land with some bush and shrub cover but limited or no tree cover, or including small trees with limited productivity. In some cases such land may derive from the degradation of forest areas.
Forestry systems	A general term used to refer to the range of possible land based vegetation systems involving trees and their associated management. Such systems would include high forest, short rotation forestry and coppice systems.
Fossil carbon	Carbon contained in mineral sources, such as fossil fuels, in which it has been stored for geologically-long periods of time, as distinct from biogenic carbon (see separate definition).
Fossil energy	Energy derived from the combustion of mineral sources (fossil fuels such as oil, natural gas and coal).
Gasification and pyrolysis conversion technologies	Processes which convert carbon-based material into synthetic combustible products. Pyrolysis is a process, which uses heat to thermally decompose carbon-based material in the absence of air or oxygen (i.e. not combustion). It produces volatile gases including synthetic combustible gas (syngas), together with a carbon-rich solid residue, for example char. Gasification is a process by which the majority of carbon in solid fuel is converted into carbon monoxide and hydrogen in the presence of oxygen. The synthesised gases produced by pyrolysis or gasification can be used in electricity or heat generation, or as a feedstock in the production of transport fuels or other chemicals.
Geological carbon	See “Fossil carbon”.
GHG, greenhouse gas	All gases which absorb infra-red radiation in the atmosphere of any planet, thereby inducing a so-called greenhouse effect which results in trapping heat which would otherwise escape into space. Due to their ubiquity and magnitude, the prominent greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Other minor gases are included such as ozone and CFCs (Chlorofluorocarbons), however the latter two are often not included as usually production is small, and the effect of these gases in small quantities has little perceived effect on climate change.
GHG emissions, greenhouse gas emissions	The production of greenhouse gases as part of natural, domestic, commercial or industrial processes and, usually, their release to the atmosphere. (See also “Absolute GHG emissions”, “Attributed GHG emissions”, “Consequential GHG emissions”, “Direct GHG emissions and indirect GHG emissions”.)
Growth rate (forest)	In the context of this report, the growth rate of forests is usually defined in terms of the potential production of stem volume expressed in terms of cubic metres of volume per hectare, i.e. $m^3\ ha^{-1}\ yr^{-1}$. It is sometimes expressed in terms of potential biomass production.

Harvest residues, harvesting residues (or felling or forest residues)	The biomass material remaining in forests that have been harvested for timber. Because only timber of a certain quality can be used by sawmills, boardmills and other processing facilities, components of woody biomass material – harvesting residues – are often left in forests during harvesting operations. Harvesting residues can include very poorly formed trees, stem tips of small diameter, branches and offcuts from the butts of stems of large trees, or from other parts of the stems of trees where there are defects. Harvesting residues may also include dead trees and rough or rotten dead wood. Often, such residues are left to decay in the forest or burned on site as part of forest management and, in particular, as part of preparation for the establishment of new trees. Harvesting residues could be collected as part of harvesting operations and used as a feedstock for forest bioenergy, and currently there is growing interest in this option.
High forest	A very common forest type where the individual trees are allowed to grow as single stems over the life of the stand, often becoming very tall and mature. This may be contrasted with coppice systems where individual trees may be cut at close to ground level on short rotations to encourage regrowth in the form of multiple shoots for the same stump/stool in suitable species.
iLUC (indirect Land Use Change)	Land use change that occurs generally as a result of market mediated responses to changes in existing patterns of land use or land management. For example, if a large area of existing agricultural land is converted to the production of bioenergy, this may limit the potential to produce food, resulting in other land areas being converted to agricultural production to meet the requirements for food. iLUC may operate locally, nationally, or trans-nationally.

Indirect GHG emissions	In general LCA terms, indirect GHG emissions refer to all emissions that are associated with a given activity but which do not arise specifically from that activity. However, the particular context will determine the exact identity of indirect GHG emissions and, since the context can change, the details of these emissions can vary. For the purposes of the quantitative assessment in this project which adopts consequential LCA, indirect GHG emissions consist of GHG emissions that occur as part of extracting, processing and transporting of an energy source, such as coal, oil, natural gas, nuclear fuel, electricity, bioenergy, etc. (including the direct combustion of fossil fuels, the provision of non-energy inputs, nitrous oxide emissions from cultivated soils and the construction/manufacture and maintenance of related infrastructure such as equipment, machinery, plant and vehicles). In this project, given its focus on the EU27 region, all direct GHG emissions resulting from the combustion of fossil fuels, and from agricultural and industrial activities within EU borders are accounted for by the VTT-TIAM model. Indirect GHG emissions associated with provision of imported fossil fuels, nuclear fuels and electricity are accounted separately. Additionally, all GHG emissions associated with the provision of all forms of bioenergy, both from sources inside and outside the EU27 region are accounted separately as indirect GHG emissions. Furthermore, indirect GHG emissions also include the displacement of other products (counterfactuals) by co-products of bioenergy sources, as well as end-of-life disposal.
Industrial roundwood	This report refers to statistics on production of industrial roundwood, as originally reported by the FAO and interpreted by the GB Forestry Commission (2012). In this context, the FAO defines industrial roundwood literally "by exception", i.e. as "all roundwood except woodfuel".
Land Use, Land-Use Change and Forestry (LULUCF)	Under the United Nations Framework Convention on Climate Change (UNFCCC, 1992), countries are required to report inventories of GHG emissions to (and removals from) the atmosphere due to human activity. These national GHG inventories are broken down into a number of sectors, each dealing with a distinct aspect of human activity as defined by the IPCC, consisting of Energy (which includes transport), Industrial processes, Solvent and other product use, Agriculture, Waste and "Land use, land use-change and forestry". Land use, land-use change and forestry (LULUCF) is an inventory sector defined by the Intergovernmental Panel on Climate Change (IPCC) that covers anthropogenic emissions and removals of GHGs resulting from changes in terrestrial carbon stocks. It covers the carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon for specified land categories (forest land, cropland, grassland, wetland, urban land and other land).

Landscape care wood	See "Arboricultural arisings".
LCA, life cycle assessment	The evaluation of the total environmental and natural resource impacts of a product or service over its complete life cycle of creation, use and disposal. However, evaluation can be restricted to certain environmental impacts, such as greenhouse gas emissions and to certain parts of the life cycle depending on the goal and scope of the assessment.
Life cycle impact assessment (LCIA)	LCIA is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" (ISO 14044:2006).
Life cycle inventory (LCI)	LCI is the phase of the life cycle assessment involving the compilation and quantification of inputs and outputs. It comprises data collection and data calculation. Data collection consists of the identification and quantification of the relevant input and output flows for the whole life cycle of a product.
Mobilising the wood resource	A term used by some commentators to describe a set of possible policies and actions which may be taken to increase the supply of harvested timber and biomass. This may involve more intensive management and harvesting of forest areas and also more efficient use and recycling of wood products.
National Renewable Energy Action Plans (NREAPs)	Plans published by all EU Member States in 2010. The plans provide details of how each Member State expects to reach the legally binding target for the share of renewable energy in their total energy consumption, as determined by the EU Renewable Energy Directive. The plans include targets, the technology mix they expect to use, and the measures and reforms they will undertake to overcome the barriers to developing renewable energy.
Policy scenario	A scenario detailing how a policy or set of related policies will be implemented and developed. The scenario includes specified activities, services and processes relevant to the policy or policies, and associated flows, e.g. of energy and GHG emissions, intended to represent the future situation following enactment of the policy or policies. (See also "business as usual scenario".)
Primary forest	FAO (2010) defines "primary forest" as "naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed".
Primary wood	In the context of this report, primary wood refers to any wood harvested from a forest, either in raw state or processed into a finished product or forming a by-product of a finished product. Specifically, it does not include wood in the form of a finished product that has come to the end of its useful life and which may either be recycled or enter the waste wood stream.
Pulpwood	A type of small roundwood often (but not exclusively) used for pulp and paper production. It can also include wood chips made directly (i.e. in the forest) from small roundwood. Pulp wood may also be used in the manufacture of wood-based panels or for bioenergy. (See "Small roundwood".)

Recycled wood	The term recycled wood is used to refer to any wood in the form of a finished product that has come to the end of its useful life and which is recycled into a new wood product (e.g. recovered sawn timber, paper, particleboard etc.).
RED	See "EU Renewable Energy Directive".
Removals	The volume of all trees, living or dead, that are felled and removed from a forest. It includes natural losses that are recovered (i.e. harvested), removals during the year of wood felled during an earlier period, removals of non-stemwood such as stumps and branches (where these are harvested) and removal of trees killed or damaged by natural causes (i.e. natural losses), e.g. fire, windblown, insects and diseases. It excludes bark and other non-woody biomass and any wood that is not removed, e.g. stumps, branches and tree tops (where these are not harvested) and other unutilised harvesting residues.
Roundwood	In the context of this report, the term roundwood is based on the FAO definition, as all roundwood felled or otherwise harvested and removed. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form, e.g. branches, roots, stumps and burls (where these are harvested).
Salvage logging	Removal and harvesting of dead, weaker or damaged trees, usually following a natural disturbance (e.g. fire, disease, storm).
Sawlog	In the context of this report, the definition of the term sawlog is based on the FAO definition as roundwood that will be sawn (or chipped) lengthways for the manufacture of sawn wood or railway sleepers (ties) or used for the production of veneer (mainly by peeling or slicing). It includes roundwood (whether or not it is roughly squared) that will be used for these purposes and other special types of roundwood (e.g. burls and roots, etc.) used for veneer production.
Sawmill co-products	The woody material left over when a sawlog is converted into sawn wood. The material consists of slabs and chunks of wood, sawdust and bark. For the purposes of this project, bark is represented as a separate category. Amongst other uses, sawmill co-products may be used for process energy within sawmills, as a feedstock to the wood-based panel industries, or as a source of bioenergy.
Scrub	See "Forest scrub".
Secondary wood	In the context of this project, secondary wood refers to any wood in the form of a finished product that has come to the end of its useful life and which may either be recycled or enter the waste wood stream.
Small roundwood	In the context of this report the term small roundwood refers to stemwood of small diameter that does not fall into the sawlog category (see above in this glossary). Small roundwood may typically be used to make fencing, or chipped to make wood-based panels or pulped to make paper. It may also be used for woodfuel.

Stemwood or "main stem"	There is no international standard definition for stemwood but, in practice, definitions used in different countries and for different types of trees are generally very similar. For example, in the UK (Forestry Commission, 2011), the definition of stemwood is given as, 'The woody material forming the above ground main growing shoot(s) of a tree or stand of trees. The stem includes all woody volume above ground with a diameter greater than 7 cm over bark. Stemwood includes wood in major branches where there is at least 3 m of "straight" length to 7 cm top diameter'.
Sustainable forest management	The concept of managing forests in a way which does not reduce the ecological, social or economic capacity of the forest for future generations. Sustainable forest management is often codified into national and international standards for management. Examples include the UK Forestry Standard and the FSC certification standard.
Sustainable yield, Sustainable yield management	The concept of managing forests in a way which does not reduce the long-term capacity of the forest to sustain a particular (volume) yield.
Top diameter	The diameter at the narrowest end of a log or length of stemwood or roundwood. Top diameter is used in the specification of different types of primary wood product such as sawlogs and small roundwood. For example, a sawlog is normally specified as having a minimum value of top diameter. Top diameter may be specified over bark or under bark.
Total tree biomass	The mass of the tree parts, both above and below-ground (stem, bark, branches, twigs, stump and roots) of live and dead trees. May also include foliage, flowers and seeds.
TPES (Total Primary Energy Supply)	TPES represents the energy produced and used within a specified region, excluding exported energy, but including energy imported into the specified region, prior to any transportation and conversion within the region as part of final consumption. This means that, for the example of the EU27 region, TPES represents: • Energy produced and used within the EU27 region, i.e. excluding any energy produced within the EU27 region and exported to elsewhere • Energy imported into the EU27 region from elsewhere.
Tropical forests	Forests in the countries situated between the Tropic of Cancer and the Tropic of Capricorn. The majority of tropical forests are broadleaved, i.e. not coniferous.
Waste wood	In the context of this report, waste wood refers to any wood in the form of a finished product that has come to the end of its useful life and which would become waste, unless recovered for recycling or use as fuel.
Woody biomass	The mass of the woody parts (stem, bark, branches and twigs) of live and dead trees, excluding foliage, flowers and seeds.

Wood fuel	In the context of this report, the term wood fuel may be used to refer to a commodity or to reported statistics. When referred to in the sense of a commodity, wood fuel means any wood (of primary or secondary origin) which is burned to generate heat or power. When referring to statistics on production of wood fuel, these were originally reported by the FAO and interpreted by the GB Forestry Commission (2012). In this context, the FAO defines wood fuel as, "Roundwood that will be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel) … It also includes wood chips to be used for fuel that are made directly (i.e. in the forest) from roundwood. It excludes wood charcoal".
Woodfuel briquettes	Wood chips, sawdust, and waste and scrap wood, possibly bark, compressed at high temperature to form a homogenised mass of wood with uniform dimensions. Most frequently used for domestic heating, some for food smoking.
Woodfuel chips	Solid wood, with or without bark, comminuted to make small to moderate size pieces of wood. Often wood chips are made to specified dimensions. Used for a range of applications including (relatively) small-scale power generation, domestic and small-scale commercial heating, food smoking. Wood chips may also be used for non-fuel uses, notably animal bedding.
Woodfuel logs	Almost unprocessed raw harvested wood, possibly small stemwood, parts of large stemwood, often parts of branches, with or without bark. Most frequently used for domestic heating, some for food smoking.
Woodfuel pellets	Wood which has been ground to sawdust and then compressed to form pellets of a size, shape and consistency. Used in large quantities for large-scale power generation, including co-firing with coal, also used for domestic and commercial heating systems, particularly automated systems.

Units of measurement

EJ	1 EJ = 1 exajoule = 10^{18} joules.
gC or gC-eq.	1 gC = 1 gram carbon or carbon equivalent.
gCO_2 or gCO_2-eq.	1 gCO_2 = 1 gram carbon dioxide or carbon dioxide equivalent.
Gha	1 gigahectare (10^9 ha) = 1 thousand million hectares.
GJ	1 GJ = 1 gigajoule = 10^9 joules.
GtC or GtC-eq.	1 GtC = 1 gigatonne (1 thousand million metric tonnes) carbon or carbon equivalent.
$GtCO_2$ or $GtCO_2$-eq.	1 $GtCO_2$ = 1 gigatonne (1 thousand million metric tonnes) carbon dioxide or carbon dioxide equivalent.
ha	1 ha = 1 hectare = 10,000 m^2.
kg a. i.	1 kg a. i. = 1 kilogram (1000 grams) of the active ingredient of a substance, typically a herbicide or pesticide.
kgC or kgC-eq.	1 kgC = 1 kilogram (1000 grams) carbon or carbon equivalent.
$kgCO_2$ or $kgCO_2$-eq.	1 $kgCO_2$ = 1 kilogram (1000 grams) carbon dioxide or carbon dioxide equivalent.
"kg x"	1 kg x = 1 kilogram (1000 grams) of the substance "x". For example, 1 kg $CaCO_2$ = 1 kg calcium carbonate.
kha	1 kha – 1 kilohectare (10^3 ha) = 1 thousand hectares.
kt	1kt = 1 kilotonne = 1 thousand (10^3) tonnes.
ktoe	1 ktoe = 1 thousand (10^3) tonnes oil equivalent. This is a unit of energy, 1 PJ = 23.8845897 ktoe.
m^2	1 m^2 = 1 square metre.
m^3	1 m^3 = 1 cubic metre.
Mha	1 Mha = 1 megahectare (10^6 ha) = 1 million hectares.
MJ	1 MJ = 1 megajoule = 1million (10^6) joules.
Mt	1 Mt = 1 megatonne = 1 million tonnes.
Mtoe	1 Mtoe = 1 million (10^6) tonnes oil equivalent. This is a unit of energy, 1 PJ = 0.0238845897 Mtoe.
MWh	1 MWh =1 megawatt hour = 1 million (10^6) watt hours. This is a unit of energy, 1 MWh = 3.6 GJ.
odt	1 odt = 1 oven dry tonne. In the case of wood, this is the mass of wood not allowing for any moisture content.
PJ	1 PJ = 1 petajoule = 10^{15} joules.
t	1 tonne = 1 thousand (10^3) kilograms = 1 million (10^6) grams.
tC or tC-eq.	1 tC = 1 tonne carbon or carbon equivalent.
tCO_2 or tCO_2-eq.	1 tCO_2 = 1 tonne carbon dioxide or carbon dioxide equivalent.
yr	1 yr = 1 year.